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# LOW-COST BUS-TUNNELS TO THE CENTRAL BUSINESS DISTRICT

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California



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FINAL REPORT



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16. Abstract To date, proposed designs of tunnels for transit buses resulted in very expensive transit guideways because of the large tunnel diameter and extensive ventilation system needed. This study was to determine if small diameter, unventilated, hence relatively inexpensive tunnels could be used for bus links between the Central Business District (CBD) and outlying areas. By using tunnels, the buses could avoid the problems of traveling on the surface streets of the CBD. The tunnels selected for the study were 16½ ft. inside diameter, the same as a single-track tunnel conventionally used for recently constructed U.S. subway rail systems. Concentration levels of exhaust emissions were within acceptable limits to a capacity of 150 diesel buses per hour for a one route-mile bus-tunnel; for a two route-mile tunnel, 54 buses per hour were acceptable. The costs of such an underground guideway are moderate ($16M per route-mile with simultaneous operation in both directions). Also, no undue operations problems will result. Furthermore, such a guideway can serve as a precursor to a Metro system since it can be converted to use by rail vehicles with little additional cost. In case it is desired to incorporate an underground station at the CBD end of the bus-tunnel, the ventilation requirements for a typical station were briefly studied. The cost estimate for the station is in the range of $26-39M (depending upon whether the design is double or single level). However, an underground station is not mandatory to the bus-tunnel concept. Based upon service, operations, and cost, the use of small diameter, unventilated tunnels for bringing diesel buses into the CBD appears attractive and should be considered.

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The author wishes to express his appreciation to Parsons, Brinckerhoff, Quade & Douglas, Inc., Consulting Engineers located in New York City for their essential contribution to this study. They calculated the ventilation requirements and cost estimates for tunnels for a wide range of operating conditions of typical urban diesel transit buses. Their report is included in its entirety in the Appendix.

## UNIT CONVERSIONS

| | | |
|---|---|---|
| in | = | 2.54 cm |
| $in^3$ | = | 16.39 $cm^3$ |
| ft | = | 0.3048 m |
| $ft^2$ | = | 0.0929 $m^2$ |
| $ft^3$ | = | 0.0283 $m^3$ |
| mile | = | 1609 m |
| mph | = | 1.609 km/hr |
| grain | = | 0.0648 gm |
| lb | = | 453.6 gm |
| Btu | = | 1055 joules |
| hp | = | 0.746 kW |
| °C | = | $\frac{5}{9}$ (°F −32) |

CONTENTS

SECTION I

# INTRODUCTION

## A. NEED FOR BUS-TUNNELS

A number of bus routes link outlying areas to the Central Business District (CBD). Many of these routes permit high block speeds until they enter the urban area. Then, not only are the buses slowed down to a crawl, they also occupy a considerable portion of the CBD surface streets, hence a further increase in traffic congestion. An example is the Southern California Rapid Transit District busway from the edge of the Los Angeles CBD out to El Monte. The average bus speed along this 10-mile long exclusive right-of-way is over 50 mph at any time of day. During work traffic periods, the automobile speed on the parallel freeway is at best 20-30 mph. At the edge of the CBD, the buses join the automobile traffic on the surface streets, thus going down to an effective speed of 10-15 mph.

If the buses could be kept on exclusive right-of-ways all the way to the ultimate stopping point in the CBD, then a number of benefits would result:

(1) Bus speeds would remain high (50 mph) all the way into the CBD, resulting in shorter travel time relative to any other mode available for the general public. This, along with the already existing lower cost to the users of public over private transportation, would attract even more riders.

(2) Buses removed from the CBD surface streets would permit better flow of auto/truck traffic.

(3) The objectionable odors of bus exhaust along the streets would be decreased in proportion to buses no longer using surface streets.

(4) The cost of operating buses would be decreased: less fuel consumption; less wear and tear since continual stops and starts would be eliminated; and fewer accidents due to operation on CBD streets.

Urban areas throughout the U.S.A. could benefit from these features of an exclusive busway all the way into the center of CBD. Of course, the exclusive right-of-way could be elevated, but this may not be practical for established urban areas, leaving the tunnel as the only feasible approach. The tunnel would have several additional benefits:

(5) The dispersion of the exhaust emitted would be restricted to the tunnel exits. If the buses did not come up to surface level in the CBD, then the emissions generated in the bus-tunnel would be emitted only from the exit in the outlying area.

(6) Adverse weather would be eliminated as a factor.

## B. PREVIOUS STUDIES

A number of previous studies have been carried out on the use of tunnels by buses (References 1-4). All of the studies resulted in a very high cost for such a busway because of the common assumptions of very high bus volume (headways on the order of three seconds or less) and that the buses would be stopping at stations all along the tunnel. These two requirements dictated tunnel designs having full transverse ventilation systems. Undoubtedly, these requirements are realistic in many instances, but, even in the cases where they are not mandatory, planners have still been discouraged from considering tunnels for buses because of the generally accepted high cost.

## C. OBJECTIVE OF THIS STUDY

This study looked at the other end of the requirement spectrum. The primary objectives were to determine the limitations of small, unventilated tunnels on bus operations and to estimate the cost of bus-tunnels. The cost of such a simple tunnel would be as low as possible. If it is still too expensive an approach to be considered, then the issue of bus-tunnels into the CBD would be closed. However, if the cost does seem attractive, then bus-tunnels can be seriously considered if the limitations upon the operations are acceptable. The secondary objectives were to indicate several basic features of an underground station and to make a rough cost estimate.

SECTION II

STUDY APPROACH

This exploratory study is based entirely upon existing applicable information. Since the existing information provides a comprehensive data base, it is felt that the conclusions reached would not be significantly altered by the use of new data or a more lengthy and in-depth analysis.

## A. ANALYSIS METHOD

An existing computer program to predict and simulate the temperature environment of rapid transit rail tunnels (Reference 5) was utilized. It was used to determine the temperatures in bus-tunnels and the station, and, with minor modifications, estimate exhaust concentrations. Details on the specific assumptions and analyses used are contained in the Appendix of this report.

## B. ASSUMPTIONS

The assumptions made result in the least complicated and least expensive system design thought to be practical. Any increase in the requirements will either result in a more costly system or one of less capacity.

### 1. Geometry

a. Tunnel. An internal diameter of 16½ ft. is assumed. This will permit a single lane of 12 ft. width with no shoulders (which is ample for bus operations). Buses operate counter-flow in the Lincoln Tunnel (NY-NJ) on lane widths of 10½ ft. (Reference 6). It should be noted that this diameter is suitable for rail transit systems since many of the modern ones in the U.S. are of this general size (Reference 5). The tunnel net cross section of 156 $ft^2$ is double that of the bus frontal area (see Figure 1).

The entire tunnel is at zero grade. The means for buses to enter this tunnel at the edge of the CBD is not considered in this study. The entry-exit portals could be in an open cut with a 5% grade.

The length of the tunnel from the edge of the CBD to the terminal station is taken to be either one or two miles. Since the station is separated from the tunnels, the incoming and outgoing tunnels act as a single long tunnel of about double the length of the distance from the station to the entry portal at the edge of the CBD. No stations are located along the tunnel.

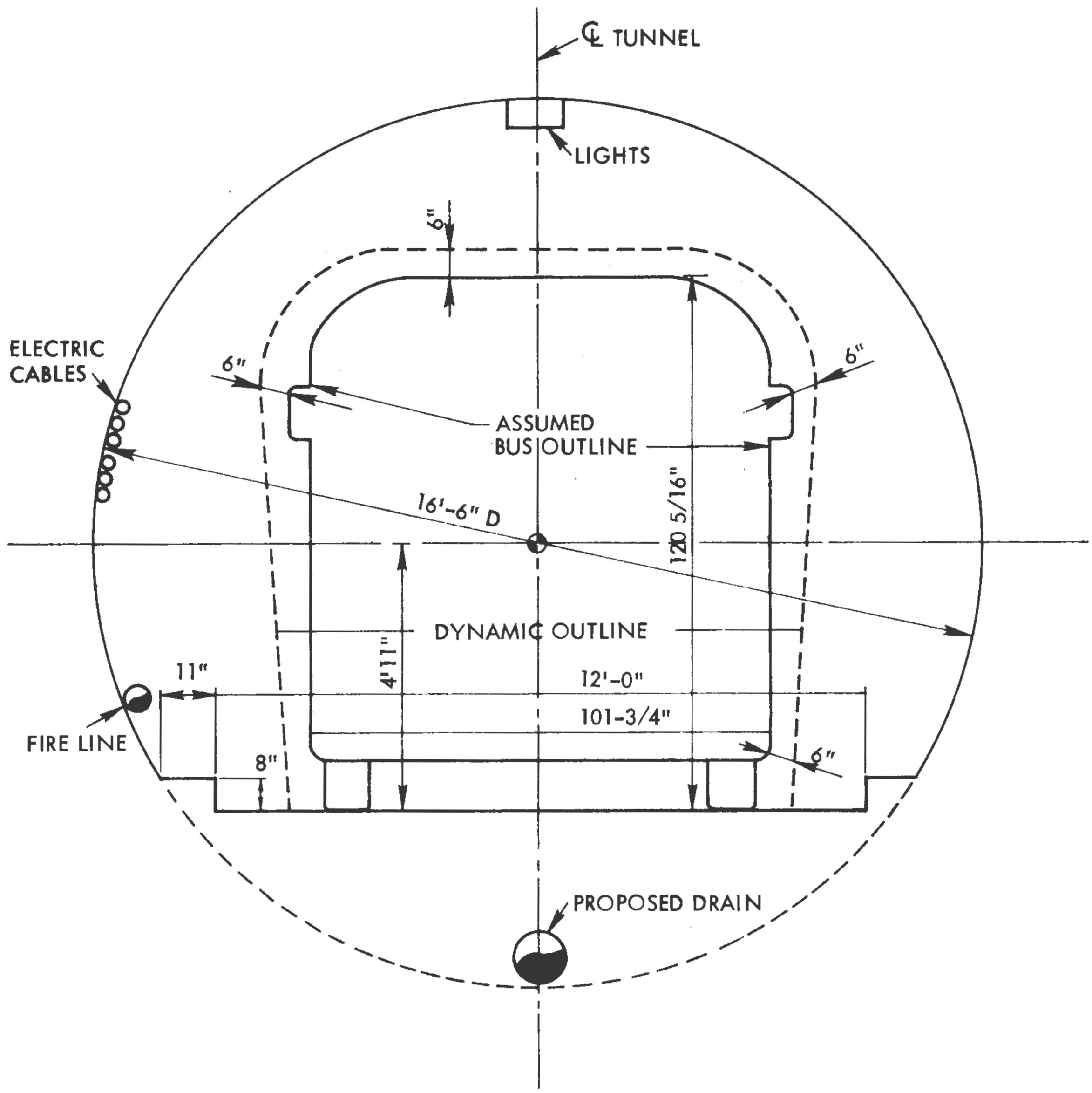


FIGURE 1. TYPICAL TUNNEL SECTION

b. Station. A major underground bus station is assumed to be located at the end of the bus-tunnel in the central portion of the CBD. It is 1000 ft. long with a cross-section area of 1500 $ft^2$. In all probability, it would be constructed by cut-and-cover with its bus platforms at the same depth as the tunnel. From considerations of exhaust concentrations and ventilation requirements, the station is made to be independent of the bus-tunnel. This can be accomplished by pressurizing the station. Also, it could be done by using doors or air curtains to separate the station from the tunnels. See Figure 2 for the relationship of the station to the tunnels.

It should be pointed out that an underground station is not mandatory to the bus-tunnel concept. The buses could be brought up to grade in the CBD to a ground-level station or continue onto surface streets to distribute and collect passengers. In such cases the appropriate tunnel lengths for acceptable levels of exhaust emission concentrations are double the route-mile lengths. This is because the air flow through each of the side-by-side tunnels is independent of the other. For example, the acceptable bus headway for a two-mile long tunnel open to the atmosphere at both ends is 24 secs. compared to the 67 sec. headway for a two route-mile tunnel guideway ending up at an underground station.

2. Operation

a. Tunnels. The buses operate through the entire length of the tunnel at constant speed. Speeds of 25-60 mph are feasible; speeds of 30-45 mph are expected to be the general operating range. Headways down to six seconds were considered.

The tunnels are to be exclusively for buses and the drivers are under complete control of an operations center. Therefore, bus speeds and headways will be controlled as a function of the existing conditions. Stalled buses are to be removed immediately by being pushed out by the following bus or by a tow truck which is constantly on duty.

b. Stations. The underground station is designed to be independent of the tunnel environment. In order to determine the ventilation requirements, the following bus operating mode is hypothesized:

(1) Inbound buses enter the station at cruising speed (equal to the constant speed through the tunnels) and brake to a stop at the end of the station.

(2) They dwell in the station for 15 minutes, of which 3 minutes is with the engine at idle. The rest of the time, the engine is either off or the exhaust is captured by a separate ventilation system, possibly a hose attached to the exhaust pipe.

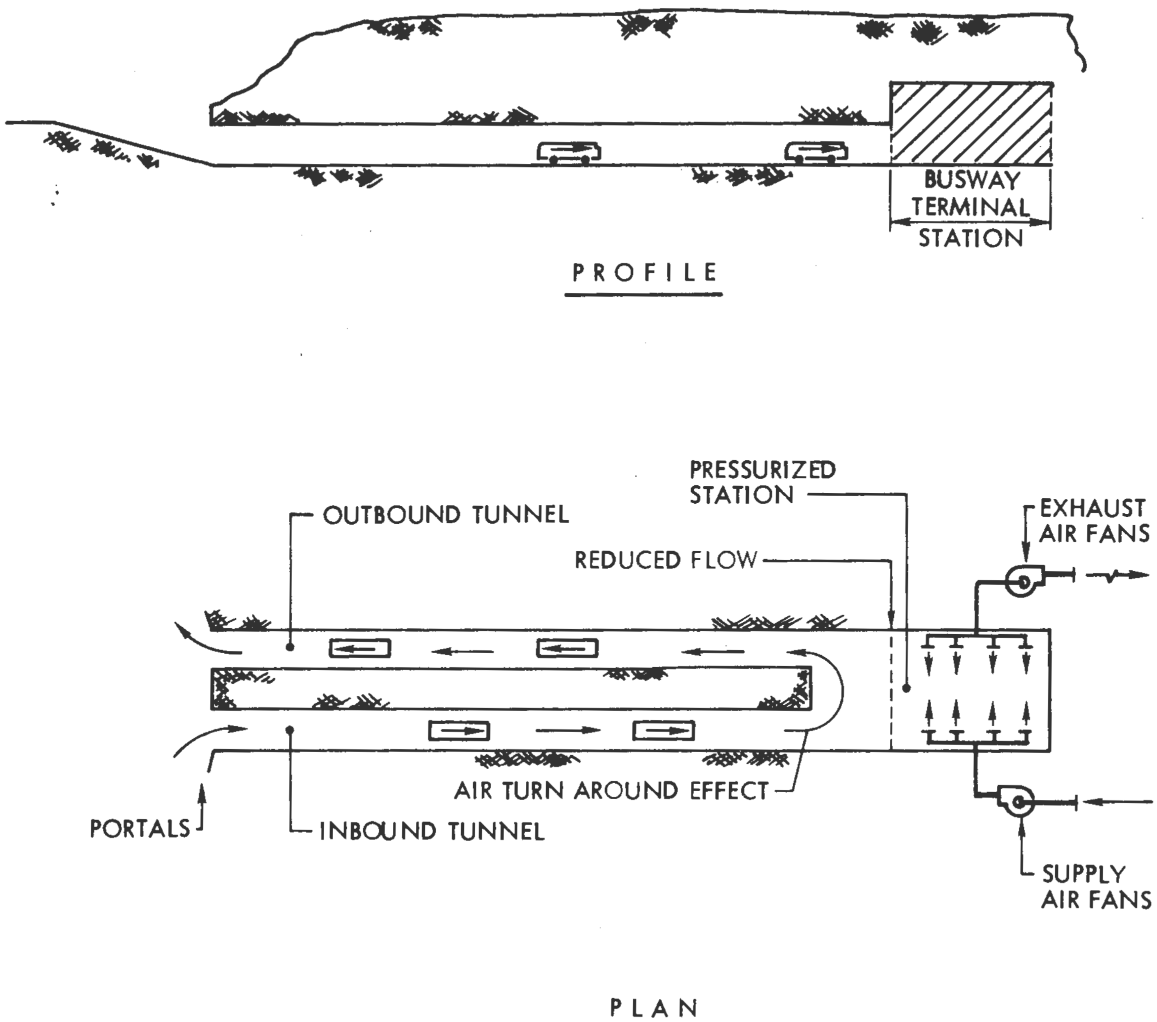


FIGURE 2. SCHEMATIC OF BUS-TUNNEL
GUIDEWAY

(3) The bus fully accelerates up to cruise speed in the station before entering the exit leg of the tunnel.

(4) The acceleration and deceleration is accomplished at 2 mph per sec.

## 3. Buses

A typical urban transit bus weighs 36,000 lbs. and has a 570 cubic-inch displacement two-stroke diesel engine using diesel fuel #1. The exhaust emissions are taken from Reference 7 and are listed in Table 1. The heat rejection for a moving bus is 400,000 Btu/hr (160 hp) and that for an idling bus is 75,000 Btu/hr (30 hp). At idle, the emissions are assumed to be 1.04 gm oxides of Nitrogen ($NO_x$) and 3.5 gm of carbon monoxide (CO) per vehicle minute.

This study was restricted to typical diesel-powered urban buses. In order to determine if the chemical pollutants of the exhaust were the critical design constraint, both emissions and heat-balance calculations were made for headways down to six seconds. Therefore, the results of this study can be extended to buses with other types of propulsion systems: all-electric buses, or buses with turbine engines since heat pollution was found not to be a factor.

Table 1. Exhaust Emissions From Diesel Buses at Constant Speed

| Speed (mph) | CO (gm per veh-mi) | $NO_x$ (gm per veh-mi) |
|---|---|---|
| idle | 3.5* | 1.04* |
| 25 | 23.8 | 19.1 |
| 30 | 19.7 | 18.5 |
| 35 | 16.9 | 18.7 |
| 40 | 15.0 | 19.7 |
| 45 | 13.9 | 21.7 |
| 50 | 13.4 | 24.8 |
| 55 | 13.5 | 29.7 |
| 60 | 14.1 | 37.2 |

*gm/veh-min

## 4. Ambient Conditions

Heating calculations for the buses in the tunnels and stations are based upon ambient dry bulb temperature of 95°F. The humidity is 75 grains per pound of air. The deep-sink temperature of the tunnel is 60°F. No winds are considered; they should normally have a negligible effect upon the analysis since the openings of the incoming and the outgoing tunnels at the edge of the CBD are in near proximity to each other and the station is aerodynamically separated from the tunnels.

5. Exhaust Pollutant Concentration Criteria

For diesel buses, the critical pollutant is $NO_x$. Satisfying the 12.5 ppm criteria for $NO_x$* will automatically satisfy the 125 ppm criteria for CO (See Appendix for details). The visibility degradation due to diesel smoke is not expected to be a problem at the assumed conditions of operation. The emissions and subsequent control of the environments of the station and the tunnels are assumed to be independent of each other. For simplicity, the same pollution concentration criteria are used for both tunnel and station environments. This may not be entirely acceptable for a number of reasons:

(1) Station concentration will be the same everywhere while tunnel concentration linearly reaches the maximum allowable criteria at the exit end of the outgoing tunnel.

(2) Time spent by the riders in the station at its maximum $NO_x$ levels would be greater than that spent in the tunnels at the location of the maximum $NO_x$ levels.

(3) Operations staff would spend even more time in the station than the riders.

6. Emergency Ventilation

Even if bus headways are long enough so that piston action is adequate to keep exhaust emission concentrations within acceptable levels, some mechanical ventilation capability is still required. An emergency ventilation system is necessary to control the direction of the spread of smoke and flames in the tunnel in the event of a bus fire. Then, people can be evacuated from the danger areas to a region of safety such as the adjoining tunnel (through cross-passages), to the station, or to the surface by the outside opening or a stairway.

An emergency ventilation rate in either direction of 175,000 cfm was selected since the 25 mph wind it would create beside the buses stopped in the tunnels would not present undue difficulty for persons walking past the buses. This flow rate can be obtained with twelve ceiling-mounted axial-flow fans located in locally enlarged sections of the tunnel (for the one-mile tunnel each fan capacity would be 140,000 cfm; for the two-mile tunnel, each would be 180,000 cfm). This ventilation rate would be sufficient to overcome the buoyant forces of a fire with a heat rate of about 600 x $10^6$ Btu/hr for tunnel grades less than 3%. This fire heat rate is conservatively high, equal to 4800 gallons of gasoline per hour.

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*Which in turn satisfies the 5 ppm $NO_2$ and 25 ppm NO ambient air quality criteria (see pages A-7 to A-9 of the Appendix).

## SECTION III

## RESULTS

### A. VENTILATION REQUIREMENTS OF THE TUNNELS

Ventilation requirements were determined for route lengths of one and two miles. However, the results can be used to determine the situation for other route lengths. This is practical because piston-action induced air flow through the tunnel is virtually independent of tunnel length, and exhaust concentrations are directly proportional to the length of the tunnel for the same bus headway and cruise speed. Piston-action air flow as a function of headway is shown in Figure 3 for a bus speed of 40 mph. Since it is proportional to bus speed, it can be adjusted for other speeds.

The total ventilation required for a one-mile tunnel in order to keep the $NO_x$ down to acceptable levels is shown in Figure 4 as a function of bus speed and headway. It can be converted to any other tunnel length simply by ratioing the headway to tunnel length. For example, the required ventilation for a two-mile bus tunnel system at 12 sec. headway is the same as for a one-mile one at 6 sec. Figure 5 shows this data in a linear manner for one and two route-mile tunnels at bus speeds of 30 and 45 mph.

Some ventilation must be available in order to take care of emergency situations such as fires even if the capacity of this bus-tunnel design is below that requiring any mechanical ventilation for normal operation. Therefore, use can be made of fans in order to increase the capacity of the bus-tunnel.

It is not straight forward to determine the contribution of piston effect in the total ventilation requirement when fans are operating. This was done only when emergency fans were operating at their design flow of 175,000 cfm. and is shown in Figure 5. The emphasis of this study is on the most simple tunnel: no vent shafts nor any fans beyond those necessary for emergency ventilation. Therefore, the contribution of piston action ventilation to total required ventilation for greater fan capacities was not determined in this study. Should there be interest in shorter headways, computer calculations must be carried out. For a first approximation at shorter headways, one can use the conservative assumption of no benefit from piston action. At ventilation speeds equal to the bus speed, there is no piston action. See Figure 5 for the headways at which this occurs.

### B. CAPACITY OF BUS-TUNNELS

The simplest situation is for bus operation through the tunnel with no mechanical ventilation, only depending upon piston action. At 45 mph, allowable minimum headways are 24 and 67 sec. for one and two-mile long tunnels, respectively. This amounts to 150 and 54 buses per

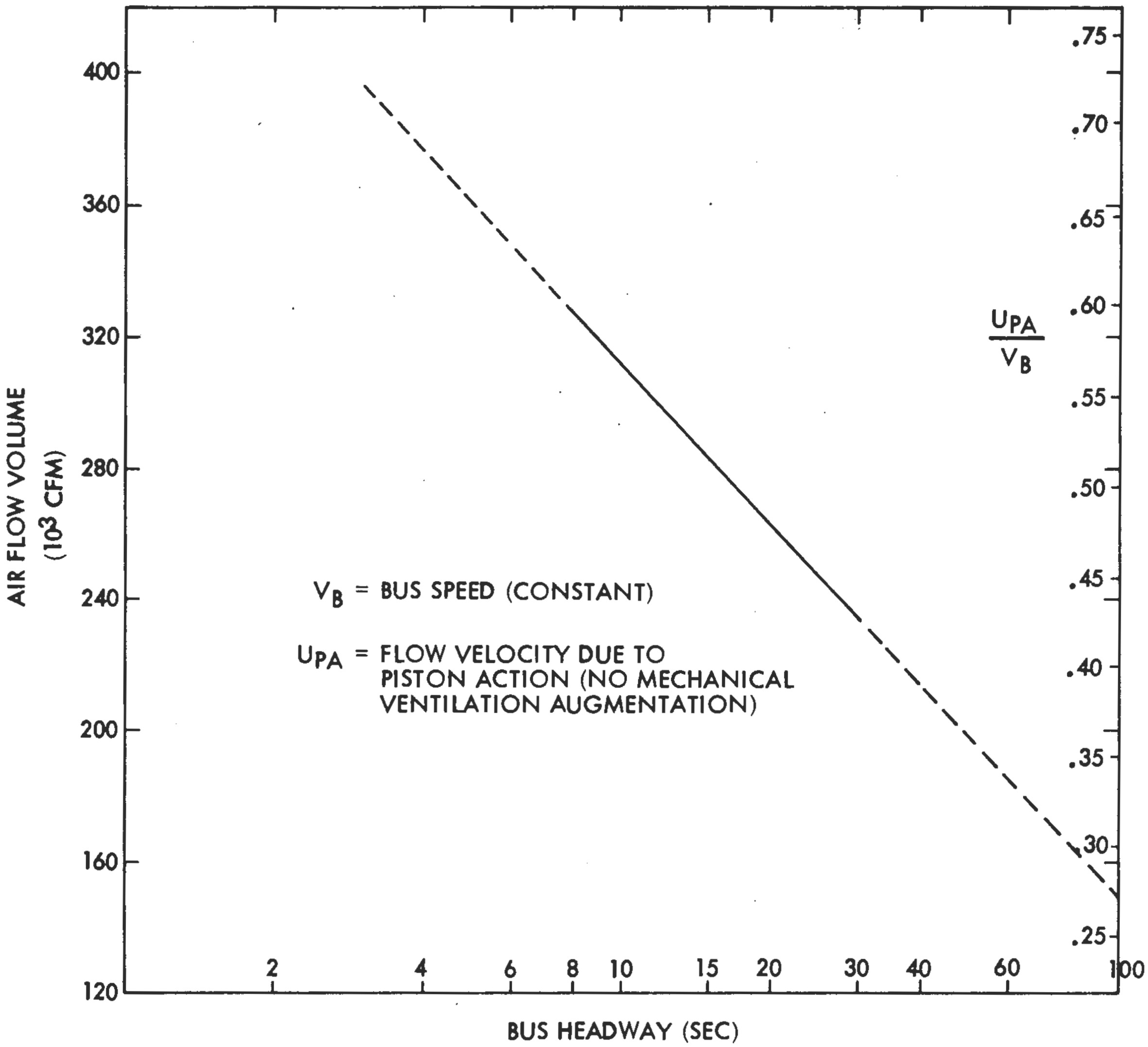


FIGURE 3. PISTON ACTION AIR FLOW THROUGH ONE-MILE BUS-TUNNEL (ESSENTIALLY THE SAME FOR TWO-MILE TUNNEL) BUSES TRAVELING 40 MPH

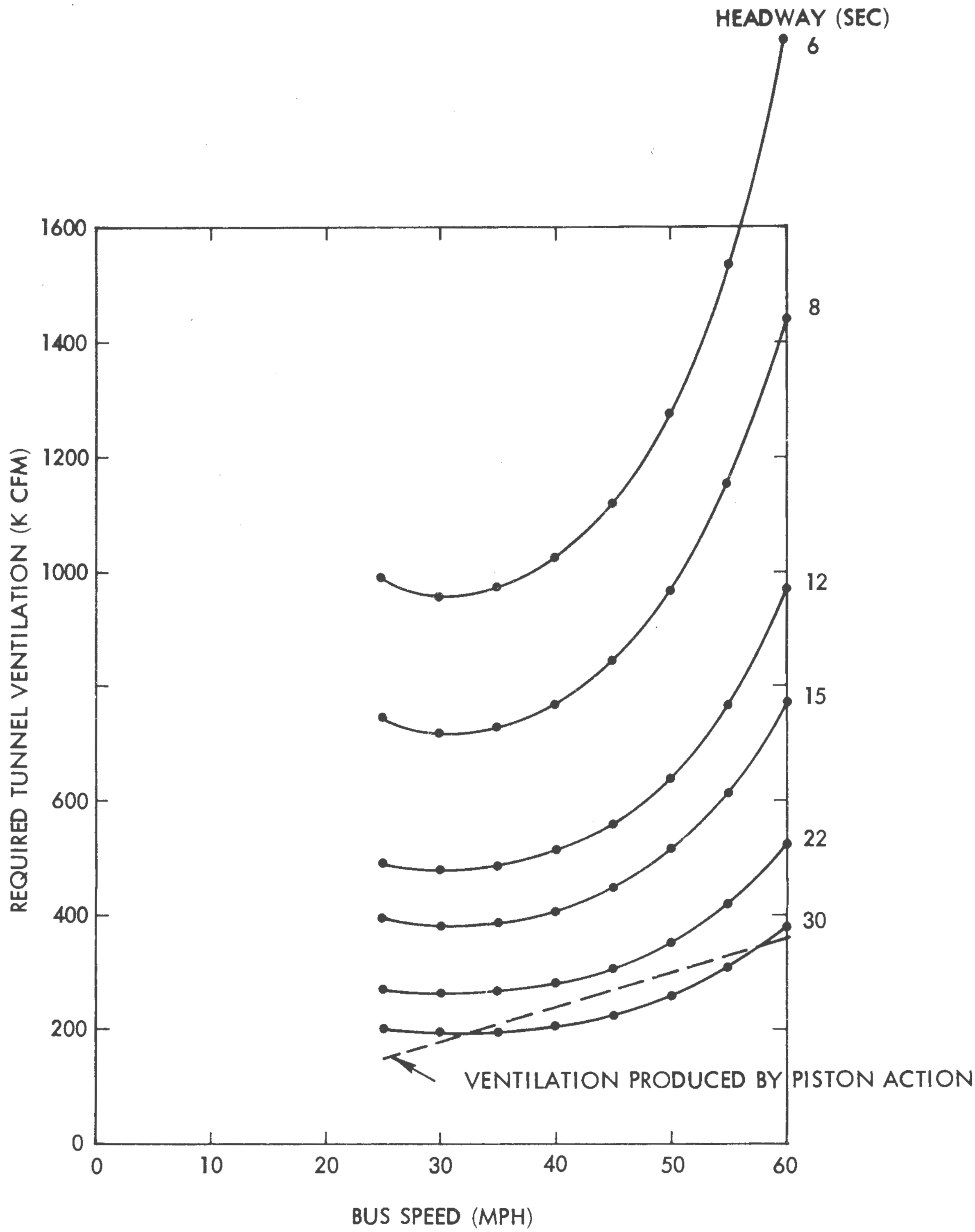


FIGURE 4. REQUIRED TUNNEL VENTILATION
FOR ONE-MILE TUNNEL

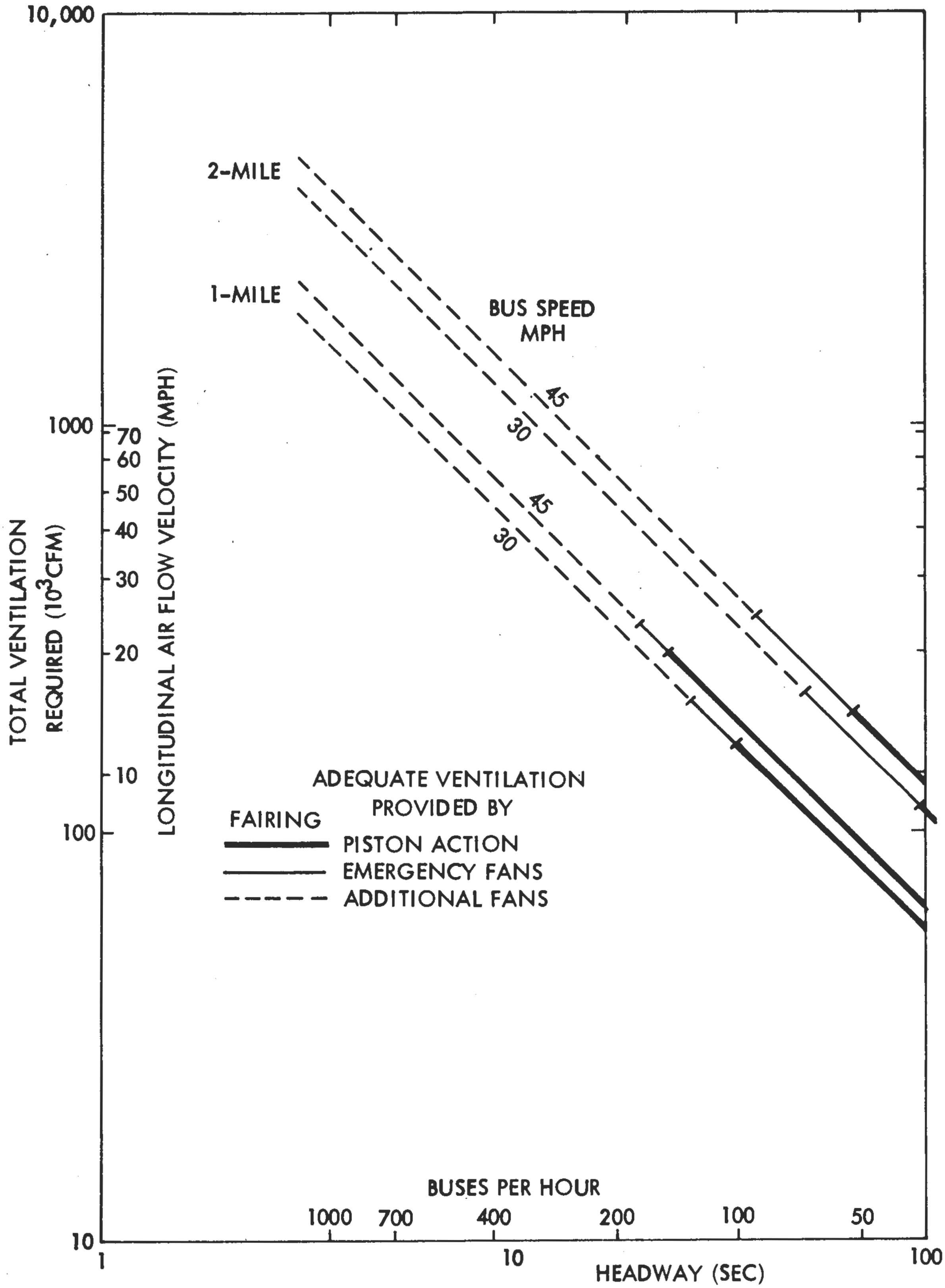


FIGURE 5. TOTAL VENTILATION REQUIREMENTS FOR BUS-TUNNELS (DIESEL ENGINES)

hour, which is a substantial level of bus operation. Use of emergency fans would decrease headways to 21 and 39 sec. respectively (increase the capacity to 171 and 92 buses per hour, respectively). Capacity in possible riders can be evaluated by assuming 40-50 riders per bus, giving a range of 2000-8000 riders per hour for the bus headways stated.

Capacities in excess of that possible with the emergency ventilation fans would necessitate additional ventilation. If the additional amount required is small, then it can be done with more ceiling and wall-mounted axial fans. If moderate, then push-pull ventilation shafts would be required. Should shorter headways be desired, then a full transverse system would be required. See the Appendix for estimates of their performance.

In determining the minimum headways, the assumption was made that no bus would regularly stop within the tunnel. In actual usage, it may be desirable to pick up and discharge passengers in the tunnel. This could be accomplished by having an occasional bus make the stop. In order to keep exhaust emissions concentration along the tunnel within tolerance and to provide adequate spacing between a stopped bus and the following bus (if a pull-out is not used), the headway behind the stopped bus and the following bus must be increased the necessary amount.

## C. VENTILATION REQUIREMENTS OF THE STATION

The resulting ventilation required to keep the $NO_x$ concentration in the underground station below 12.5 ppm is shown in Figure 6 as a function of bus speed and headway. The requirements are moderate for cruise speeds of 45 mph and headways of 15 sec., just 300,000 cfm. However, in order to maintain adequate positive pressure in the station, air supplied would have to be around 350,000 cfm, with the difference being exhausted through the tunnels.

## D. COST ESTIMATES

### 1. Tunnel

A wide variety of cost estimates exist for the basic tunnel in the same type of favorable geologic conditions. These are shown in Table 2. It is not in the scope of this study to evaluate them. An evaluation which appears in Reference 10 indicates that the lowest one is the most realistic; it is consistent with the actual costs experienced by the Metropolitan Water District of Southern California on a number of individual applicable projects of lengths from about 4000 ft. to 30,000 ft.

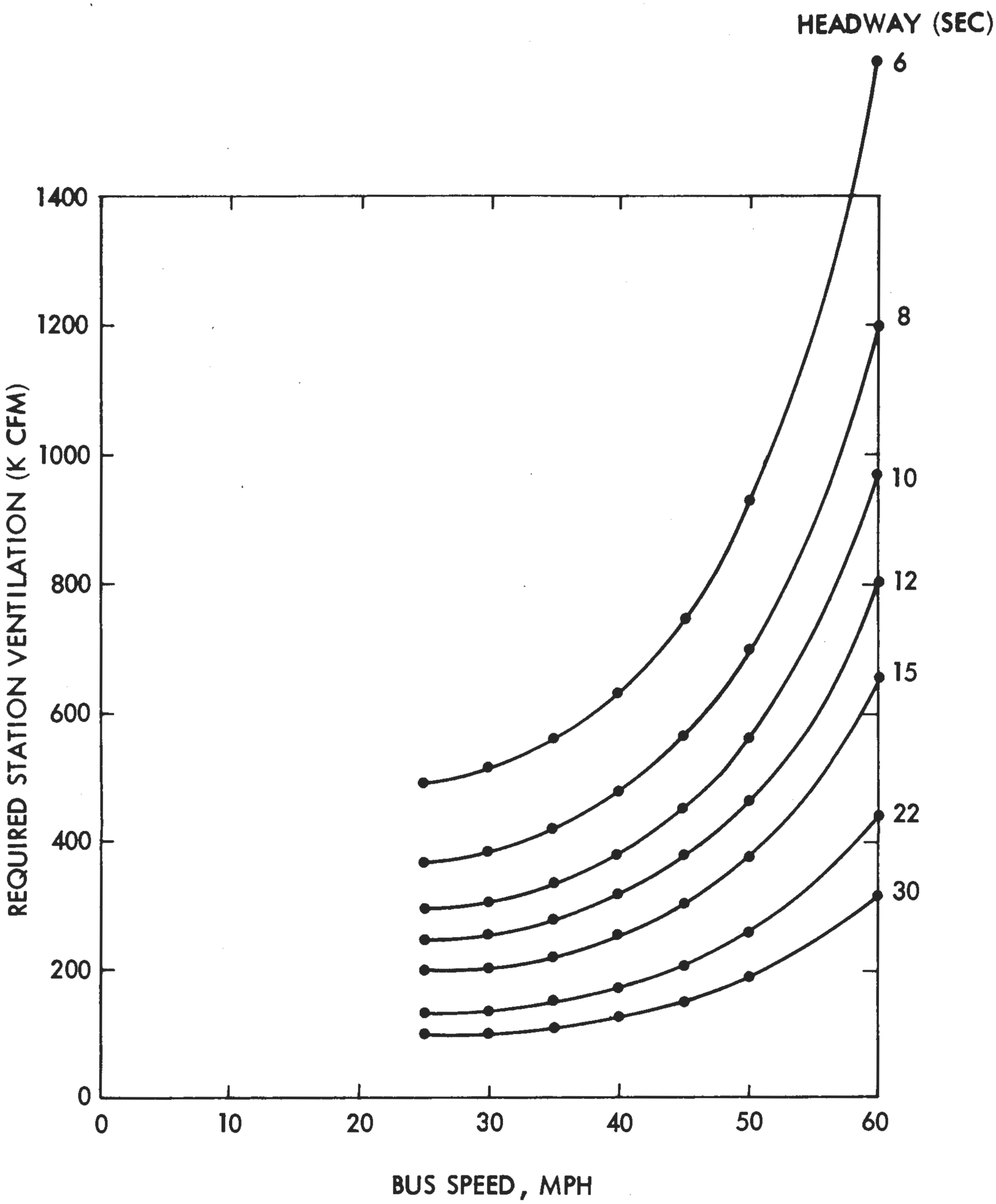


FIGURE 6. REQUIRED STATION
VENTILATION

Table 2 Estimated Costs of the Most Simple Bus-Tunnel

| Route Length (miles) | Cost of Basic Tunnel ($ per ft) | Source | Cost of Emergency Ventilation (Appendix) ($M) | Total Cost of Bus-Tunnel ($M) |
|---|---|---|---|---|
| 1 | 1737 | Ref. 8 | 1.62 | 19.96 |
| 1 | 1330 | Ref. 9 | 1.62 | 15.66 |
| 1 | 2675 | Appendix | 1.62 | 29.87 |
| 2 | 1737 | Ref. 8 | 1.93 | 38.62 |
| 2 | 1330 | Ref. 9 | 1.93 | 30.02 |
| 2 | 2675 | Appendix | 1.93 | 58.43 |

The total cost in Table 2 includes the tunnel guideway, the emergency ventilation system (axial fans, enlargements in the tunnel ceiling to accommodate the fans, and all associated wiring and controls).

To limit $NO_x$ concentration to acceptable levels should it be desirable to have shorter bus headways than are permissible for the most simple tunnel design, it is necessary to incorporate additional ventilation capability in the design of the bus-tunnel. The additional cost is nominal as long as a push-pull ventilation system is adequate (the air flow velocities in the tunnel are below 60 mph). For example, only about $5.32M additional is required for shafts and fans to accommodate bus headways down to nearly 6 sec. in a one route-mile bus-tunnel. In the two route-mile tunnel studied, an additional $5.51M is required to get headways as low as 8 sec. These are small cost increments for the large increases in bus capacities. Still lower headways (or bus stops along the tunnels) would necessitate full transverse ventilation systems, resulting in guideway total costs of about 2½ times those listed in Table 2.

To determine the cost of a complete system, it is necessary to include costs of outside bus access to the tunnels should a ramp be required. Also, the cost of the underground station with its ventilation system must be included. A first-cut estimate on station costs can be obtained from References 8 and 11 extrapolated to a 1000 ft. long subway rail station of the required width. The estimate is about $37M for the structure of 100 ft x 1000 ft single level station (of Figure 2) plus about $2M for the ventilation system to handle buses operating on 24 sec. headways. The cost of the station can be decreased by about $13M to $24M if it is designed with two levels, thus requiring a width of only 55 ft.

## E. OTHER TYPES OF PROPULSION SYSTEMS

Information derived in this study can be directly applied to buses having propulsion systems other than diesel such as the turbine engine (having less than one-half of the exhaust emissions of diesel engines - Reference 1) and electric (primary emission is heat). For example, the minimum headway for turbine buses operating at 45 mph in the one route-mile tunnel system without the need of any mechanical ventilation can be determined as follows: As a first approximation, headway can be decreased by the same ratio as the decrease in critical emission. But, due to increased piston action caused by additional buses, headway is even less.

From Figures 3 and 5, it can be seen that piston action of 281,000 cfm is sufficient for controlling exhaust emission of diesel buses operating on their minimum acceptable headway of 24 sec. By the iterative use of piston action data in using the same two figures, it can be seen that a headway of 9½ sec. would generate proper piston action to balance total critical exhaust emission of the increased number of buses, each one emitting only half of the critical emission of the standard diesel bus. This means that a decrease in the exhaust emissions of $NO_x$ by a factor of two will more than double the allowable capacity of buses in the bus-tunnel; 2½ times, to be exact.

## SECTION IV

## CONVERSION TO A RAIL SYSTEM

An important aspect of the bus-tunnels proposed in this study is the similarity in size and shape of the tunnels to the newer subway-train transit systems throughout the United States. This means that it would be practical to convert the bus-tunnel to a subway system even if there was no such intention originally. Furthermore, there would be a minimum of "wasted" costs since most of the features of the bus-tunnel are needed for the subway system. Perhaps, the ceiling-mounted emergency fan system (at a cost of under $2M even for the two route-mile system---four miles of actual tunnel) would not be suitable, but discarding that system would not result in much "waste". This would not be the case for bus-tunnels costing 2½ times more because they have full transverse ventilation systems (References 1-4). The high-cost ventilation systems would be almost totally "wasted".

If a conversion to rail is contemplated at the time of initial construction, it would be desirable to use a push-pull ventilation system having shafts to the surface instead of ceiling-mounted fans since mid-line vent shafts comprise the usual environmental control systems for rail transit systems. Such shafts will greatly increase the bus capacity of the tunnel guideway. Because of the similarities of bus-tunnels with subways, the conversion process could be carried out with a minimum of degradation in the service to the transit riders along the established route.

# SECTION V

## SUMMARY AND CONCLUSIONS

Unventilated tunnels are operationally practical as exclusive guideways for bringing buses into the CBD. The airflow generated by the buses will permit up to 150 diesel buses per hour (24 sec. headways) through a one route-mile underground guideway without exceeding acceptable concentrations of exhaust emissions. A two route-mile version of this bus-tunnel will still accommodate up to 54 buses per hour (67 sec. headways). Modified propulsion systems such as those using turbines or electric motors will further increase the number of buses per hour that can go through the tunnel while maintaining adequate air quality from exhaust emissions and/or air temperature considerations.

Such tunnels will alleviate congestion upon surface streets while dramatically decreasing bus travel time by over 3 minutes per route-mile. This, in turn, should increase patronage. Since operation of each vehicle can be completely directed by a control center, it is possible to utilize the bus-tunnel in an efficient and safe manner even when problems occur. There need not be any stop-and-go driving, which is a cause of emissions problems and high fuel consumption rates in most highway tunnels utilized by cars and trucks. Scheduling problems resulting from a disabled bus in the tunnel could be corrected when that bus is removed by turning on the emergency fan system and operating the backed-up buses on shorter headways.

The cost of these unventilated 16½ ft. D tunnels (one for each direction of traffic) is $15M per route-mile in the favorable geology assumed. The number of buses per hour that can use this tunnel guideway can be doubled by adding several mid-line ventilation shafts with fans at a nominal cost increase of about $2M per route-mile.

The cost of an underground station located in the Central Business District is estimated to be in the range of $26-39M, depending on whether it is double- or single-level. It should be pointed out that an underground station is not mandatory to the bus-tunnel concept. The buses could be brought up to grade in the CBD to a ground-level station and/or continue onto surface streets to distribute and collect passengers.

It is practical to convert bus tunnels (having a capacity of 15,000 riders per hour for 12 sec. headways and 50 riders per bus) to subway train use (having quadruple the capacity but with an order of magnitude less drivers). The conversion of bus-tunnels with ceiling-mounted fans would take somewhat more effort and money than those with ventilation shafts.

Based upon service, operations and cost considerations, the use of small diameter, unventilated tunnels to bring diesel buses into the CBD appears attractive. Therefore, it is recommended that this bus-tunnel concept be seriously considered in the planning of improved public transportation systems.

# SECTION VI

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* Proprietary

# ALTERNATE CONCEPTS FOR TUNNEL TRANSIT SYSTEMS

## BUS-TUNNEL GUIDEWAY

Prepared by

Parsons Brinckerhoff Quade & Douglas, Inc.

Consulting Engineers

New York, N.Y.

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for

California Institute of Technology
Jet Propulsion Laboratory

Pasadena, California

## 1. INTRODUCTION

In certain metropolitan areas the use of buses for mass transit is more desirable than other modes of transportation. The effects of traffic tie-ups on scheduling and public acceptance come into play once a mass transit bus system comes into the heart of an urban area. A solution to the traffic problem is to use tunnels to carry buses into the central business district. The purpose of this study is to investigate the ventilation requirements for a working bus tunnel.

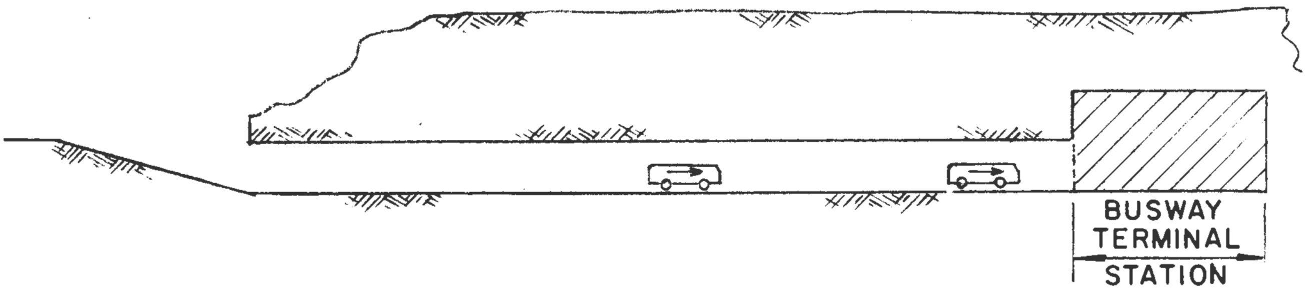
## 2. BASIC ASSUMPTIONS

The basic assumptions used to evaluate the prototypical bus tunnel system included the following:

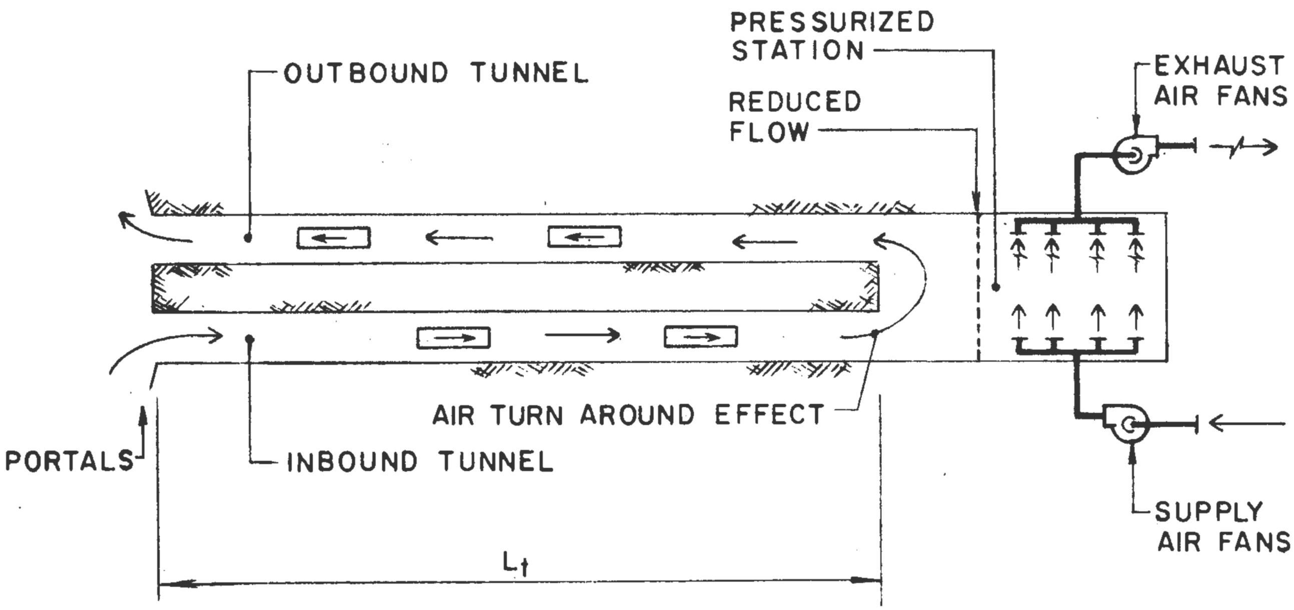
a. The system is used exclusively for buses. Figure 1 shows a schematic of the bus tunnel system. The terminal station has separate entry and exit tunnels.

b. The tunnel has a single lane without shoulders. Figure 2 shows a typical bus tunnel cross section. The lane width is 12 feet and the tunnel has a nominal inside diamter of 16'-6".

c. Stalled buses are removed immediately by tow trucks or pushed out by the following bus.

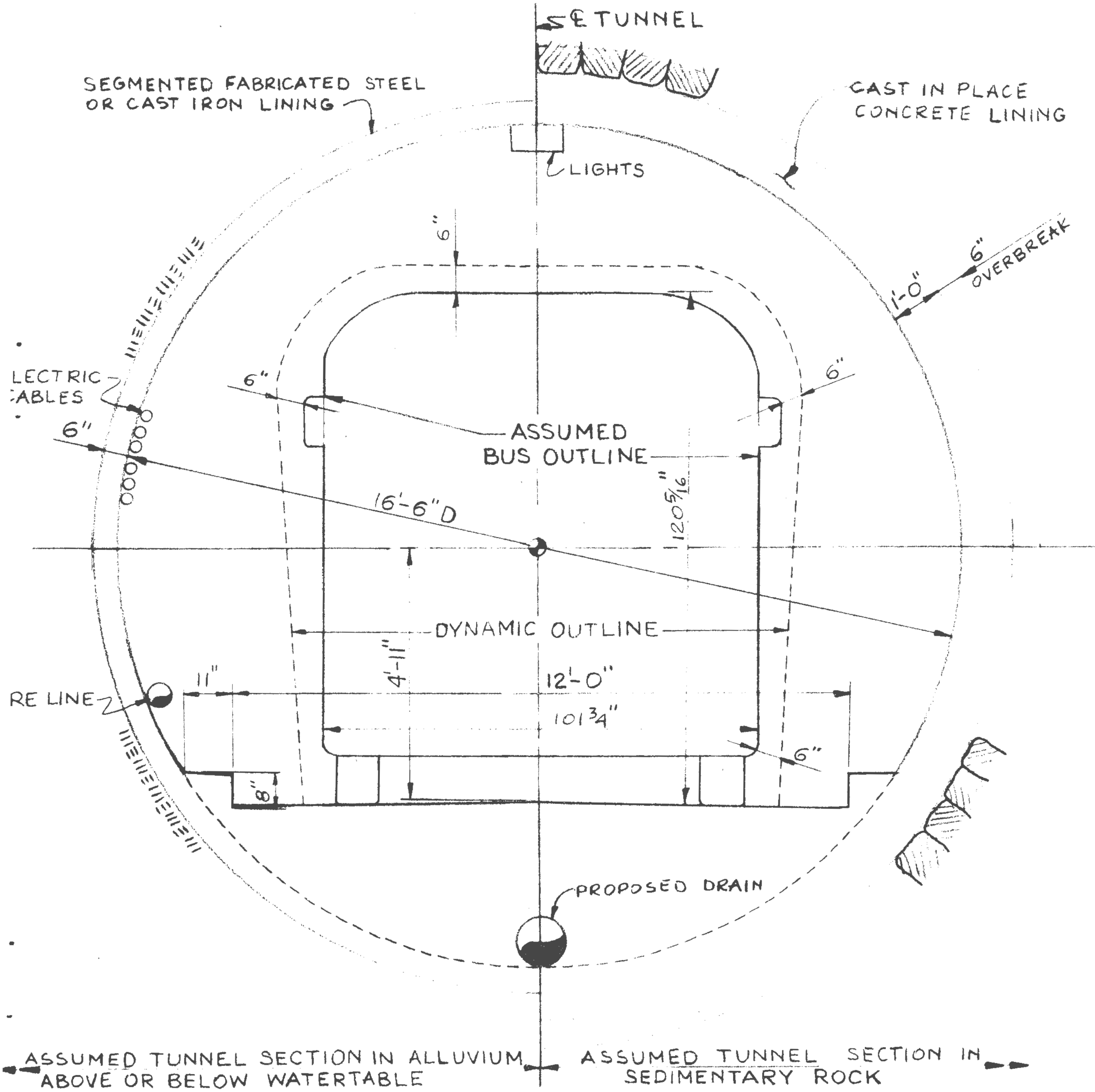



PROFILE




PLAN

FIGURE 1
BUSWAY
PLAN & PROFILE
SCALE: NONE




TYPICAL TUNNEL SECTION

SCALE: 3/8" = 1'-0"

FIGURE 2

d. The tunnels are one or two miles long.

e. There is a zero grade throughout the tunnel.

f. No intermediate stations are located within the tunnel, and a terminal bus depot is located at the end of entry tunnel. The terminal station is 1000 feet long with a cross section area of 1500 square feet.

g. All buses use diesel engines.

h. The bus has a cross-sectional area about half that of the tunnel. The analyses used a bus cross section area of 78.6 square feet and a tunnel area of 156.2 square feet.

i. Drivers are under complete control of the tunnel operations center; hence speeds and headways may be well-controlled.

j. The buses operate through the entire length of the tunnel at constant speed. 25 to 60 mph operations are feasible and 30 to 45 mph operations are probable.

k. Headways of six seconds or greater are feasible and 6 to 30 second headways are probable.

l. The ambient dry bulb temperature is $95^\circ$ F and the deep sink temperature is $60^\circ$ F.

m. The heat rejection for a moving bus is 400,000 Btu/hr (160 bhp) and that for an idling bus is 75,000 BTU/hr (30 bhp).

## 3. DIESEL BUS EMISSION FACTORS

The major pollutants emitted by diesel buses are the oxides of nitrogen ($NO_x$) and carbon monoxide (CO). An accepted approach for computing vehicle emissions may be found in "Mobile Source Emission Factors", EPA Office of Transportation and Land Use Policy, Washington, D.C., June 1977. The emission rates computed herein used this approach with the following assumptions:

a. Heavy duty, diesel-powered vehicles (HDV) are used for buses.

b. Weighting Factor for Diesel Powered HDV's, Fraction of Annual Travel from Census of Transportation, Truck Inventory and Use Survey. Department of Commerce, Bureau of the Census, Washington, D.C., 1974.

c. Vehicle engine displacement of 570 cu in.

d. Bus operating weight of 36,000 lbs.

e. Humidity 75 gr.

The following are the carbon monoxide and oxides of nitrogen emission factors estimated for the calendar year 1978:

| Speed (mph) | CO (gm/mi-veh) | $NO_x$ (gm/mi-veh) |
|---|---|---|
| 25 | 23.8 | 19.1 |
| 30 | 19.7 | 18.5 |
| 35 | 16.9 | 18.7 |
| 40 | 15.0 | 19.7 |
| 45 | 13.9 | 21.7 |
| 50 | 13.4 | 24.8 |
| 55 | 13.5 | 29.7 |
| 60 | 14.1 | 37.2 |

The 60 mph data is not as accurate as the other. The upper limit of the EPA data base is 55 mph and they recommend that caution be used in extrapolating above it. The bus emissions at idle are 1.0378 gm/(veh-min) for $NO_x$ and 3.5 gm/(veh-min) for CO.

The oxides of nitrogen emitted by diesel-powered buses are found mainly in the form of nitric oxide (NO), lesser amounts of nitrogen dioxide ($NO_2$) and only traces of other oxides. Since NO usually continues to oxidize to $NO_2$ in the air at ordinary temperatures, there is no way to predict with accuracy the amounts of each compound present at any given time. $NO_2$ in the presence of sunlight will undergo reactions with a number of organic compounds to produce the effects associated with photochemical smog. Since this study is confined to a tunnel this phenomenon will not occur. NO is considerably less toxic than $NO_2$. It acts as an asphyxiant by reducing the normal oxygen concentration of the air. On the other hand, $NO_2$ kills by pulmonary edema following exposures to 150-200 ppm for 10 minutes or more. It may also cause bronchitis and broncho-pneumonia. Both NO and $NO_2$ are formed when combustion temperatures exceed $2000^{\circ}$ F, but usually less than 0.5% is $NO_2$. More $NO_2$ is formed when the atmospheric oxygen ($O_2$) reacts with NO, but with the dilute concentrations of NO found in ambient air this process is slow without the aid of sunlight. However, during the initial stages of exhaust gas dilution, the concentration of NO is high and forces the reaction to proceed more rapidly until the NO concentration falls to 1 ppm or less. During this interval, approximately 10% of the NO oxidizes to $NO_2$.

Criteria for Oxides of Nitrogen

The EPA document "Air Quality Criteria for Nitrogen Oxides" (AP-84) suggests maximum short-term exposures of 25 ppm for NO and 5 ppm for $NO_2$.

In order to establish a criteria for $NO_x$ it was assumed the effects of NO and $NO_2$ are additive. The threshold level value (TLV) of the mixture is determined by the equation:

$$\left[\frac{C_{NO}}{TLV_{NO}} + \frac{C_{NO_2}}{TLV_{NO_2}}\right] \leq 1.0$$

Using a threshold level for NO of 25 ppm and for $NO_2$ of 5 ppm the above equation becomes:

$$\left[\frac{C_{NO}}{25} + \frac{C_{NO_2}}{5}\right] \leq 1.0$$

It is further assumed that the oxides of nitrogen are composed of NO and $NO_2$ only, then:

$$C_{NO} = x\,C_{NO_x} \quad \text{AND} \quad C_{NO_2} = (1-x)\,C_{NO_x}$$

$$\text{WHERE} \quad 0 \leq x \leq 1.0$$

$$\therefore \left[\frac{x\,C_{NO_x}}{25} + \frac{(1-x)\,C_{NO_x}}{5}\right] \leq 1.0$$

$$\text{OR} \quad C_{NO_x}\left[\frac{5-4x}{25}\right] \leq 1.0$$

Solving for the different concentrations of $NO_x$ the following results were obtained:

| $C_{NO_x}$ | x | $C_{NO_2}$ | $C_{NO}$ |
|---|---|---|---|
| 25 | 1.0 | 0 | 25.00 |
| 20 | 0.94 | 1.20 | 18.80 |
| 15 | 0.83 | 2.55 | 12.45 |
| 13.89 | 0.80 | 2.78 | 11.11 |
| 12.50 | 0.75 | 3.13 | 9.31 |
| 11.36 | 0.70 | 3.41 | 7.95 |
| 11.0 | 0.68 | 3.50 | 7.50 |
| 10 | 0.63 | 3.70 | 6.30 |

The criteria of 12.5 ppm of $C_{NO_x}$ was used because it affords the traveling public and the busway employees freedom from harmful effects while still assuming a reasonable percentage of $NO_2$ .

Criteria for Carbon Monoxide

The Federal Highway Administration (FHWA) criteria is 125 ppm.

Choice of Pollutant to be Analyzed

An examination of the $NO_x$ criteria (12.5 ppm) and the CO criteria (125 ppm) and their relative emmission rates (same order of magnitude) led to the conclusion that satisfying the $NO_x$ criteria will also satisfy the CO criteria. Hence $NO_x$ concentrations were analyzed.

## 4. TUNNEL ENVIRONMENTAL ANALYSIS

Tunnel Air Temperatures

A Subway Environment Simulation (SES) computer program output showed for a 1-mile-long tunnel with 40-mph buses operating at 30 second headways, that the resultant tunnel temperature would decrease from the ambient temperature at the portal (95$^{\circ}$ F) to about 85$^{\circ}$ F adjacent to the busway station. A review of the output concluded for the project range of headways, tunnel lengths, and vehicle speeds that the tunnel air temperature will not exceed ambient temperature and thus would be satisfactory. This assumes that the tunnel emergency ventilation fans would be used during warm weather periods to bring cool night-time air into the tunnels to reduce the temperature of the tunnel walls, thereby recharging the tunnel "heat sink" by removing a portion of the daily accumulation of heat. This conclusion would also be true for electrically powered buses because of the greater efficiency of their motors.

Tunnel Oxides of Nitrogen Concentrations

In general, the maximum concentration of $NO_x$ occurring in the tunnel is given by:

$$C_{NO_x}(h_w, U_v, L_t, \sigma, \cdots) = \frac{E'_{NO_x}(U_v) \times U_v \times \left(\frac{L_t}{h_w \times U_v}\right)}{\rho_{AIR} \times Q(h_w, U_v, L_t, \sigma, \cdots)}$$

Keeping all extraneous variables constant reduces this equation to:

$$C_{NO_x}(h_w, U_v, L_t) = \frac{E_{NO_x}(U_v) \times \left(\frac{h_t}{h_w}\right)}{\rho_{AIR} \times Q(h_w, U_v, L_t)}$$

where,

$E'_{NO_x}(U_v)$ = $NO_x$ emission factor at bus speed, $U_v$, gm/(veh-mile)

$Q$ = tunnel airflow, cfm

$h_w$ = bus headway, sec/veh

$U_v$ = bus speed, mph

$L_t$ = tunnel length, miles

The effect of tunnel length on the tunnel airflow is neglible because of the length of all the buses in the tunnel divided by the tunnel length is a constant for a given headway.

$Q = Q(h_w, U_v)$, for piston ventilation and finally,

$$C_{NO_x}(h_w, U_v, L_t) = \frac{E'_{NO_x}(U) \times \left(\frac{L_t}{h_t}\right)}{\rho_{AIR} \times Q(h_w, L_t)}$$

By using the above equation one can generate from the results of a baseline system the resulting $NO_x$ concentration for any combination of variables. This assumes that the functional variation of tunnel air flow rate can be established. The SES program output provided the required relation for the baseline system which had $h_w$ = 30 sec/veh, $U_v$ = 40 mph and $L_t$ = 1 mile. Therefore in general :

$$C_{NO_x}(h_w, U_v, L_t) = C_{NO_x}(30, 40, 1) \times \left[\frac{E'_{NO_x}(U_v)}{E'_{NO_x}(40)}\right] \times \left(\frac{30}{h_w}\right) \times \left(\frac{L_t}{1}\right) \times \left(\frac{Q(30, 40)}{Q(h_w, U_v)}\right)$$

But $C_{NO_x}(30,40,1) = 10.9$ ppm, $E'_{NO_x} = 19.7$ gm/veh-mile), $Q(30,40) =$ 234,225 cfm and $Q(h_w,U_v) = Q(h_w,40)U_v/40$. Substituting gives:

$$C_{NO_x}(h_w, U_v, L_t) = 10.9\left[\frac{E'_{NO_x}(U_v)}{19.7} \times \left(\frac{30}{h_w}\right) \times \left(\frac{234225}{Q(h_w,40)}\right) \times \left(\frac{40}{U_v}\right) \times L_t\right]$$

This is Equation 1, where,

$Q(h_w,40)$ = tunnel air flow (cfm) for headway, $h_w$, and bus operating at 40 mph. The values are found in Figure 3.

The value of $C_{NO_x}$, is the <u>maximum</u> concentration in the tunnel. It occurs at the exit of the outbound tunnel.

The maximum $NO_x$ concentrations for various bus speeds and headways for a one mile tunnel were calculated using Equation 1. They are shown in Figure 4. The $NO_x$ criteria of 12.5 ppm is plotted as a base reference.

The tunnel ventilation required to satisfy the design criteria of 12.5 ppm of $NO_x$ was calculated for the various bus speeds and headways for a one mile long tunnel. Equation 1 was used in the following derivation.

RESULTS TAKEN FROM 40 MPH SES SIMULATIONS – ONE MILE TUNNEL

| $h_w$ | $Q(h_w, 40)$ |
|---|---|
| 8 | 325,415 |
| 15 | 284,808 |
| 22 | 254,693 |
| 30 | 234,225 |

△ SES SIMULATIONS

⊙ EXTRAPOLATIONS

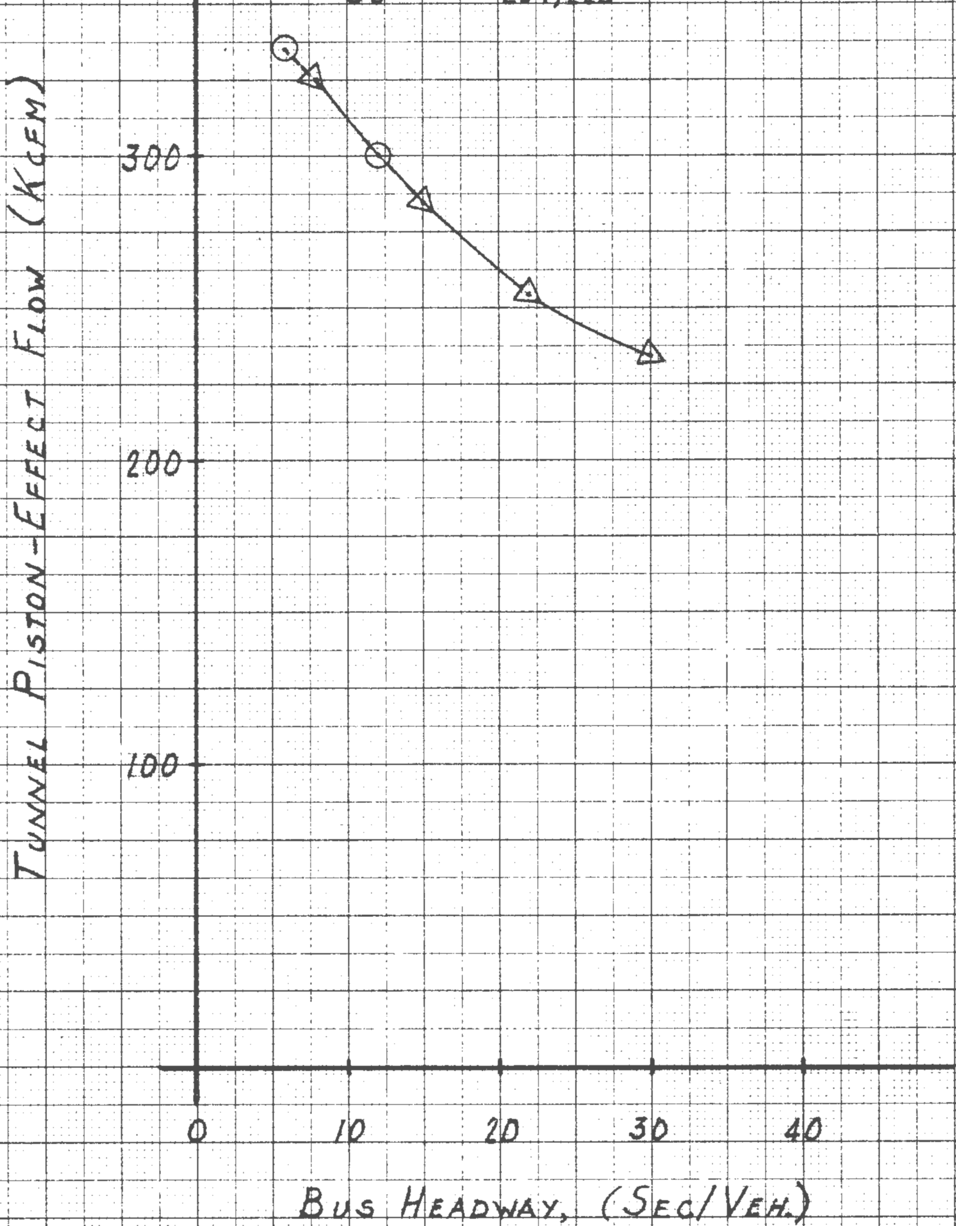



FIGURE 3 TUNNEL AIRFLOW (Q)

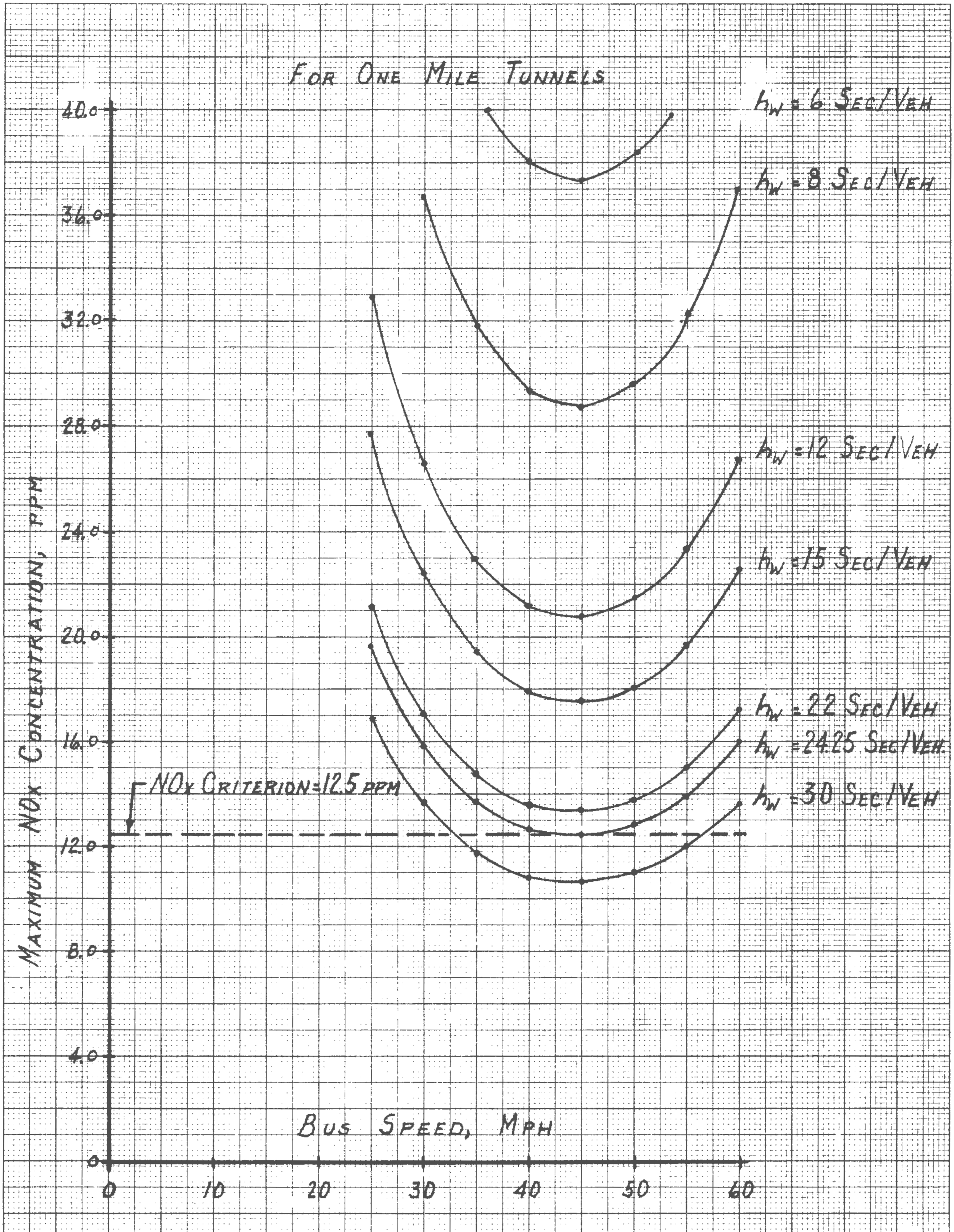



FIGURE 4 MAXIMUM NOx CONCENTRATION FOR 1-MILE TUNNELS

$$Q_{required} = C_{NO_x}(h_w,U_v,L_t)Q(h_w,U_v)\ /12.5$$

Substituting in Equation 1 gives: $Q_{required} = 311{,}032 L_t E_{NO_x}/h_w$

Figure 5 shows the results of these calculations. The required volume of tunnel ventilation includes that caused by piston action. For headway-speed combinations lying below the dashed line, piston action alone is sufficient for ventilation of the one mile approach tunnels.

The ventilation that must be added by fans, $Q_{fans}$, is determined by $Q_{fans} = Q_{required} - Q_{piston}$. Based on bus travel at 40 mph the quantity of air moved by piston action is:

$$Q_{piston} = Q(h_w,U_v) = U_v Q(h_w,40)/40$$

It should be noted that mechanical ventilation will decrease the amount of air flow attributable to piston action; the greater the fan-induced airflow, the less the piston action airflow until it becomes zero when the fan-induced air flow speed reaches the bus speed. Except for several conditions, the above interaction was not precisely determined in this study.

The two mile long approach tunnel to the bus terminal station was next studied. Equation 1 indicates that the maximum $NO_x$ concentration

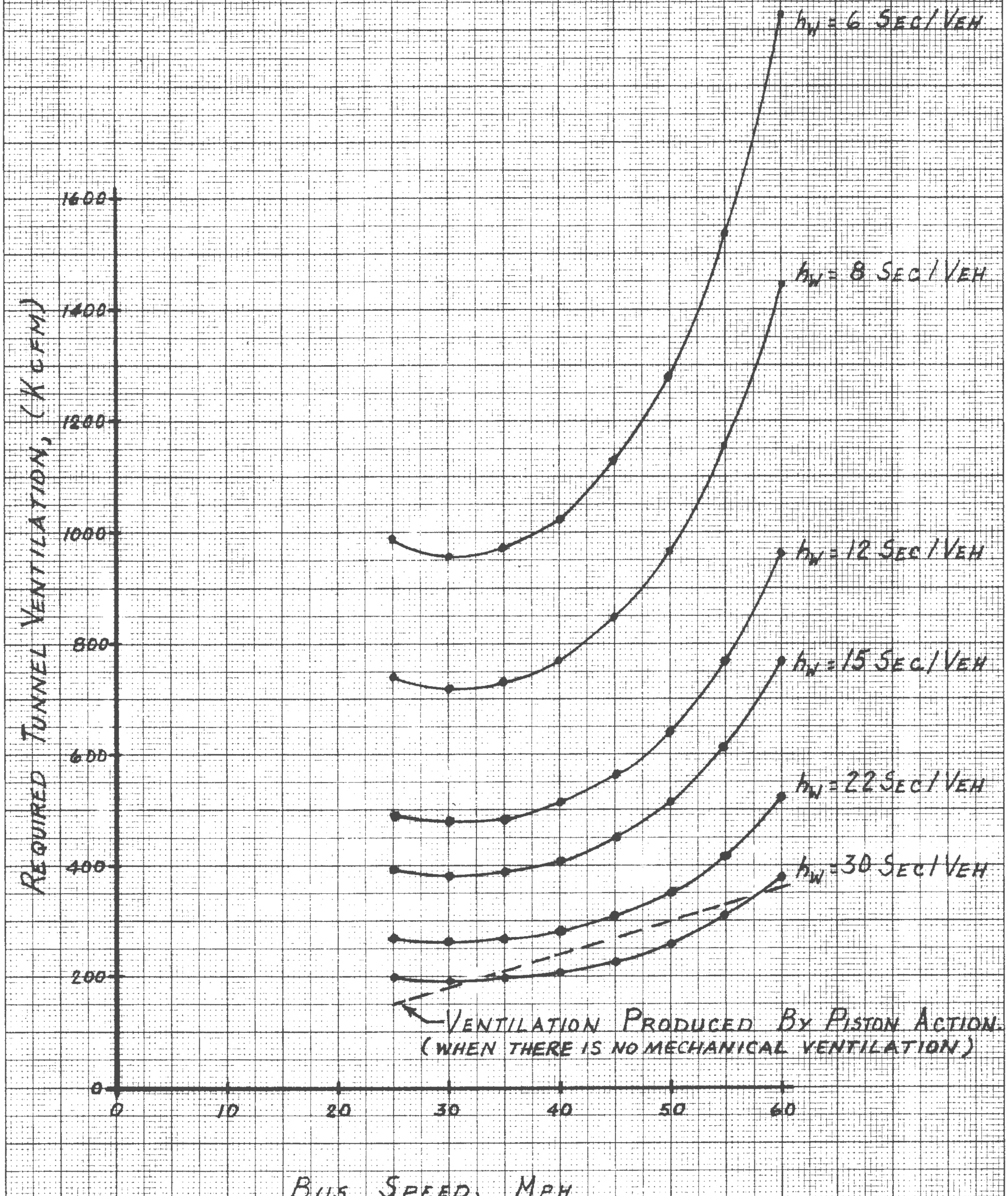



FIGURE 5 REQUIRED TUNNEL VENTILATION FOR ONE MILE TUNNELS

is directly proportional to tunnel length. Therefore, if the tunnel length is doubled, the concentration will double and the required ventilation will double. The piston action ventilation remains virtually the same. The values of the total ventilation required were calculated for the two mile long tunnel. The results of the calculations are shown in Figure 6 for various bus speeds and headways.

## Discussion

Figure 4 shows that for any given headway, the minimum $C_{NO_x}$ occurs at $U_v$ = 45 mph. The variation of maximum $NO_x$ concentration, $C_{NO_x}$, with bus speed is nearly parabolic and symmetrical about $U_v$ = 45 mph. As a consequence of the parabolic relation with bus speed, the $C_{NO_x}$ curve intersects the criterion line, $C_{NO_x}$ = 12.5 ppm, at two points. This indicates that for a given headway there exists a range of bus speeds for which no mechanical ventilation is required. For example, for a headway of 30 sec/veh, no mechanical ventilation is required if the bus speed is between about 34 mph and 56 mph. Buses traveling at speeds below 34 mph do not generate enough piston ventilation to dilute the $NO_x$ exhausted. On the other hand, buses traveling above 56 mph emit more $NO_x$ than can be diluted by the corresponding piston ventilation.

Figure 4 indicates that there exists a minimum bus headway below which mechanical ventilation will always be required. This minimum headway can be determined by using Equation 1 and solving for the

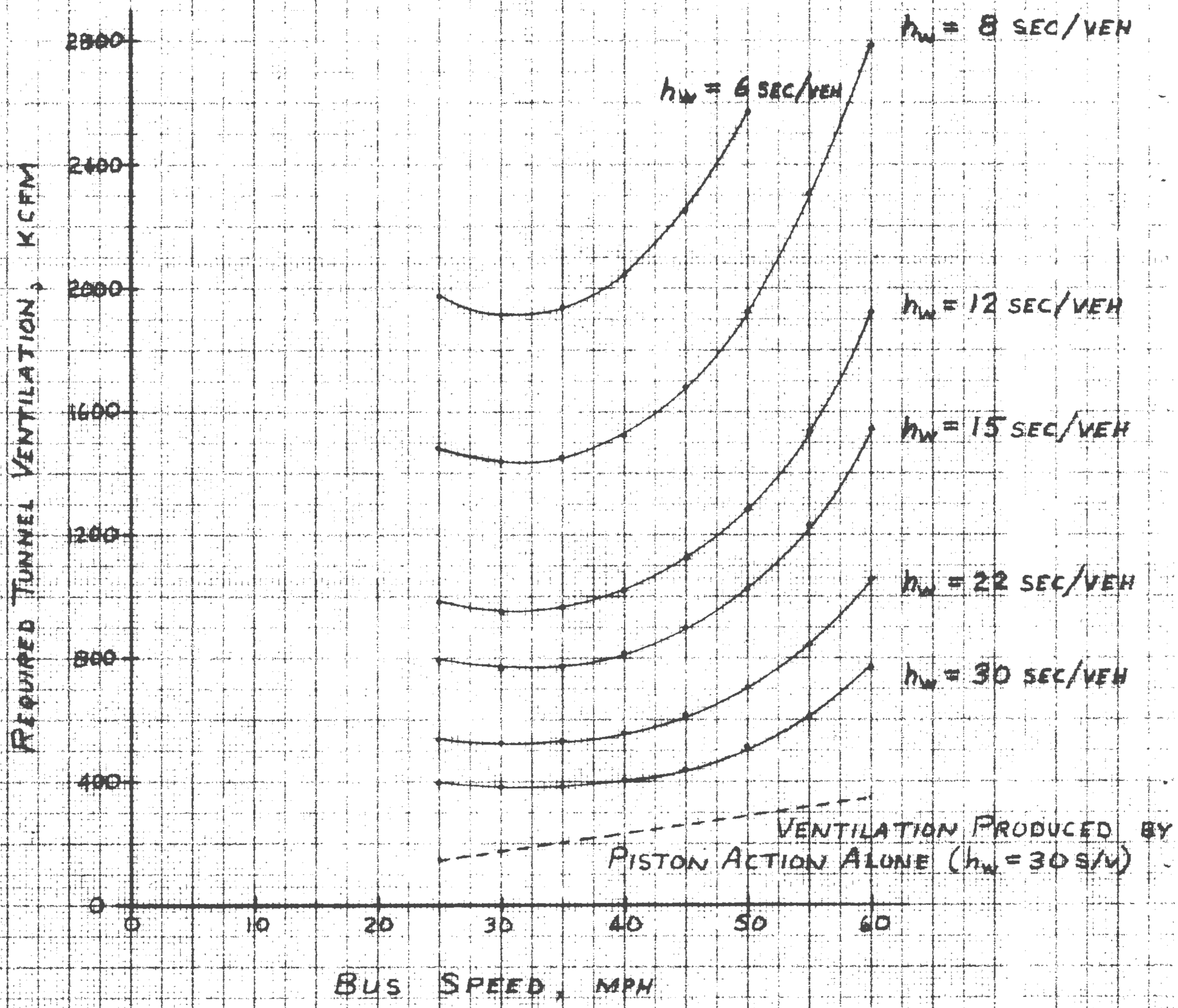



FIGURE 6 REQUIRED TUNNEL VENTILATION FOR TWO MILE TUNNELS

headway at which the maximum tunnel $NO_x$ concentration, $C_{NO_x}$, equals the maximum allowable concentration ($C_{NO_x}$ = 12.5 ppm) for the case when buses are traveling at 45 mph. The minimum headway is approximately 24 seconds.

Figure 7 shows the maximum $NO_x$ concentration, $C_{NO_x}$, as a function of bus speed for various bus headways. It displays the same information as Figure 4, for different bus headways. Figure 7 was used in turn to define the boundaries of the shaded region in Figure 8 which, for a given headway, gives the range of bus speeds for which no mechanical ventilation is required.

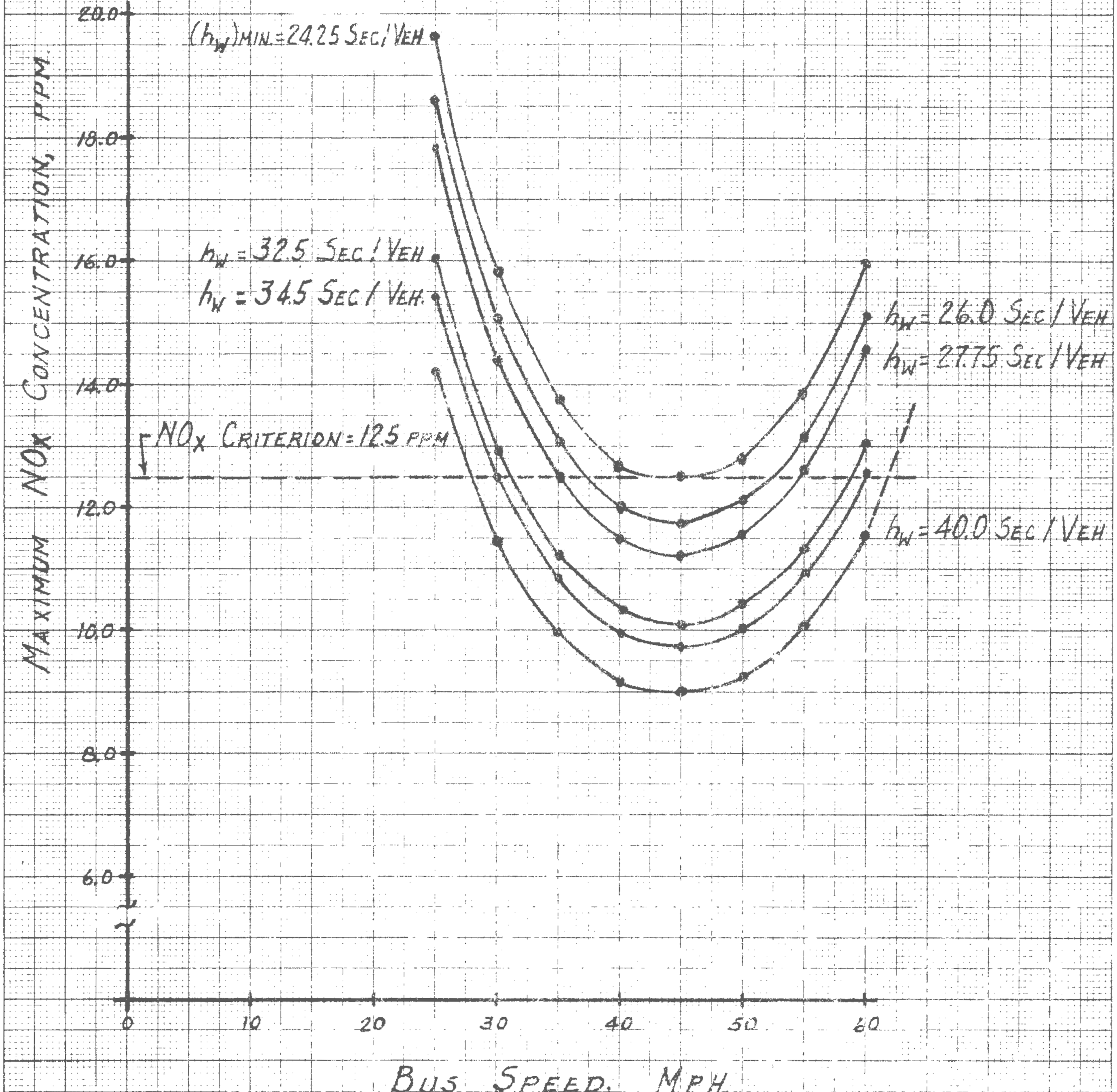



Figure 7 Maximum $NO_X$ Concentration For One Mile Tunnels

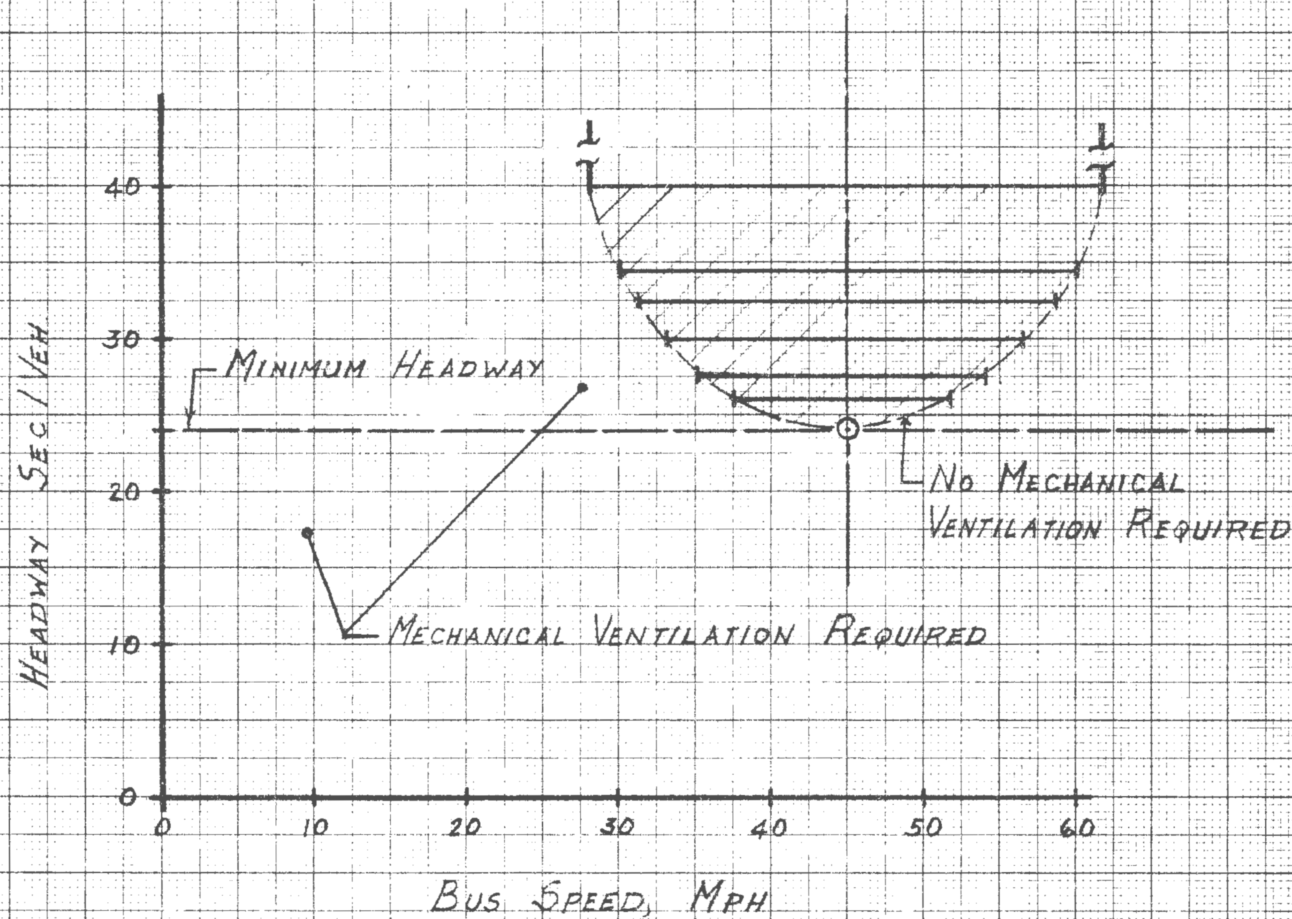



Figure 8 Range Of Bus Speeds, For Which No Mechanical Ventilation Is Required. For 1 Mile Tunnels.

## 5. TERMINAL ENVIRONMENTAL ANALYSIS

### Terminal Oxides of Nitrogen Concentrations

The station is considered to be independent of the tunnel environment for the purposes of this analysis. This decoupling of the station and tunnel can be achieved practically by operating the station ventilation system at a positive pressure relative to the tunnel.

Inbound buses traverse the length of the station at cruising speed, brake to a stop at the end of the station, dwell for a specified time, turn and exit the station at cruising speed.

It is further assumed:

1. 15 minute dwell in the station.

2. On the average, a bus will idle for 3 minutes.

Therefore, the buses idle for, 3 min./15 min. = 20% of the time they are stopped in the station, or equivalently, 20% of the buses in the station are idling at any time.

For a 30 second headway, 30 buses are in the station.

$$\text{i.e., the number of buses} = \frac{15 \text{ MIN.}}{\left(30 \frac{\text{SEC}}{\text{BUS}}\right) \times \left(\frac{1}{60} \frac{\text{MIN}}{\text{SEC}}\right)} = 30 \text{ BUSES}$$

and the number of buses idling = (0.2) x 30 buses = 6 buses.

In general,

$$\text{The number of buses idling} = \frac{(0.2) \times (15 \text{ MIN})}{h_w \times \left(\frac{1}{60} \frac{\text{MIN}}{\text{SEC}}\right)}$$

$$= \frac{180}{h_w}$$

The amount of $NO_x$ exhausted by the buses in the station consists of the amount emitted by the idling buses and the amount of $NO_x$ emitted by the buses entering and leaving the station. The emission factor while idling is 1.0378 gm/(veh-min). Converting to lbs/hr gives:

$$E'_{NO_x} = \left(1.0378 \frac{gm}{\text{VEH-MIN}}\right) \times \left(60 \frac{\text{MIN}}{hr}\right) \times \left(\frac{2.2046}{1000} \frac{Lb/Kg}{gm/Kg}\right)$$

$E'_{NO_x} = 0.137 \frac{Lb}{hr}$ while idling and the total emissions from all the idling buses is:

$$E_{NO_x} = E'_{NO_x} \times (\text{No. OF IDLING BUSES}) = 0.137 \frac{Lb}{\text{VEH-HR}} \times \frac{180}{h_w}$$

$$E_{NO_x} = \frac{24.71}{h_w}$$

The $NO_x$ emission factor while the bus is moving at a constant speed is a function of the bus speed.

$$E'_{NO_x} = E'_{NO_x}(U_v) \quad \text{IN} \quad gm/(\text{VEH-MILE})$$

CONVERTING TO LbS/hr

$$E'_{NO_x} = E'_{NO_x}(U_v) \times U_v \times \frac{2.2046}{1000}$$

$$E'_{NO_x} = 2.2046 \times 10^{-3} U_v E_{NO_x}(U_v)$$

and, the total emissions from all the buses operating within the station are:

$$E_{NO_x} = \left[ E'_{NO_x}(U_V) \times U_V \times (2.2046 \times 10^{-3}) \times 2^{*} \times \frac{(t_1 - t_2)}{hw} \right]$$

WHERE $E_{NO_x}$ IS IN Lb/hr

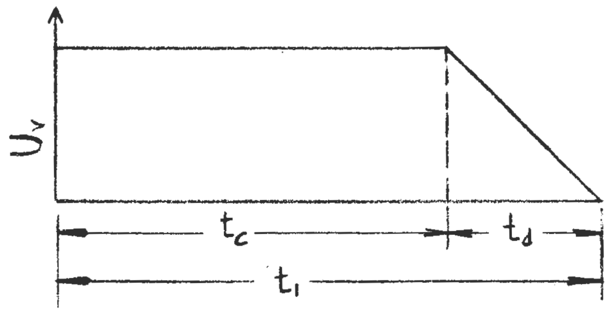
where:

$t_1$ = time required for a bus to traverse station and brake for stop, (sec.)

$t_2$ = time required for a bus to accelerate to speed and exit station, (sec.)

* Note: The factor 2.0 accounts for the increased emissions during acceleration and while the buses maneuver for turning and parking. It was derived on a judgement basis.

The time required for the bus to traverse the station and brake for a stop is:




$t_d = \left(\frac{U_v}{A_d}\right)$ = RATE OF DECELLERATION

ALSO $S_d$ = THE STOPPING DISTANCE

AND $S_c$ = THE DISTANCE COVERED AT CONSTANT SPEED

$S_d = \frac{A_d t_d^2}{2}$  $S_c = L - S_d$ WHERE L IS THE STATION LENGTH

$$\& \ t_c = \frac{(L - S_d)}{U_d}$$

$$t_1 = (t_c + t_d) = \frac{(L - \frac{1}{2} A_d t_d^2)}{U_d} - \frac{U_v}{A_d}$$

$$t_1 = \frac{L}{U_v} + \frac{U_v}{2A_d}$$

If the rate of acceleration is assumed to equal the rate of acceleration, then the time required for the bus to accelerate to speed, $U_v$ and exit the station will be equal to the time required for the bus to enter and stop. Therefore,

if, $A_d = A_a$  $t_1 = t_2$

For $L = 1000$ FEET, $A_c = A_d = 2$ mph/SEC

$$t = \left[\frac{1000}{U_v \times 1.47} + \frac{1}{2}\left(\frac{U_v}{2}\right)\right] = \frac{1000}{1.47\,U_v} + \frac{U_v}{4}$$

$E_{NO_x}$ THEN BECOMES

$$E_{NO_x} = (2.0)(2.2046 \times 10^{-3})(E'_{NO_x}(U_v) \times U_v)\left(\frac{2}{hw}\left(\frac{1000}{1.47 U_v} + \frac{U_v}{4}\right)\right)$$

$$E_{NO_x} = \left[6.0125 + 2.2046 \times 10^{-3} \times U_v^2\right] \times \left[\frac{E'_{NO_x}(U_v)}{hw}\right]$$

gm/(veh-mile).

## Required Station Ventilation

The amount of fresh air required in the station to satisfy the criterion of 12.5 ppm of $NO_x$ is given by:

$$Q_{REQ} = \frac{\Sigma E_{NOx}}{0.075\left(\frac{Lbs}{CU\,FT}\right) \times 60\left(\frac{MIN}{HR}\right) \times 12.5 \times 10^{-6}\left(\frac{Lbs\ NOx}{Lb\ AIR}\right)}$$

$$Q_{REQ} = 1.78 \times 10^{4}\, \Sigma E_{NOx}$$

WHERE $\Sigma E_{NOx}$ IS THE SUM OF THE EMISSIONS FROM THE IDLING AND OPERATIONAL BUSES

SUBSTITUTING IN THE PREVIOUS EQUATIONS GIVES

$$Q_{REQ} = (1.78 \times 10^{4}) \times \left[\frac{24.71}{h_w} + \left(6.0125 + 2.2046 \times 10^{-3} U_v^{2}\right)\frac{E'_{NO_x}(U_v)}{h_w}\right]$$

$$Q_{REQ} = \frac{1}{h_w}\left[429283 + E'_{NO_x}(U_v)\left(106890 + 39.1929\, U_v^{2}\right)\right]$$

Example:

for $h_w$=30 sec/veh, $U_v$=40 mph and $E_{NO_x}$(40)=19.7 gm/(veh-mi)

$$Q_{REQ} = \frac{1}{30}\left[439283 + 19.7\left(106890 + 39.1929 \times 40 \times 40\right)\right]$$

$$Q_{REQ} = 126{,}013\ CFM$$

Figure 9 shows the required station ventilation as a function of various bus speeds and headways. The effect of supplying these quantities of outside air would be to maintain the station at about the ambient temperature. Again night-time air circulation would be used to recharge the heat sink.

For example, the volume of fresh air required for a bus headway of 30 seconds per vehicle, a 40 mph speed is approximately 130,000 cfm. Fresh air would be supplied at 150,000 cfm to maintain a positive pressure to reduce the $NO_x$ pollutants of the tunnel busways entering the station. Air would be exhausted at 130,000 cfm.

## 6. TUNNEL VENTILATION REQUIREMENTS

### Emergency Operations Ventilation Air Velocity Criteria

The emergency ventilation system must be able to control the direction of the spread of smoke and flames in the busway tunnel in the event of a bus fire so that people can be evacuated to a point of safety which, depending on the evacuation concept chosen, is usually the nearest available tunnel-to-tunnel cross passage or exit to the surface. An emergency ventilation rate of 175,000 cfm in either direction has been chosen. The basis for this selection was the limitation of the air velocity in the bus-tunnel annulus (a tunnel cross section of 156.2 square feet and a frontal projected area of a bus of 78.6 square feet) to a maximum of 2200 fpm (25 mph). This is the maximum air velocity that a person

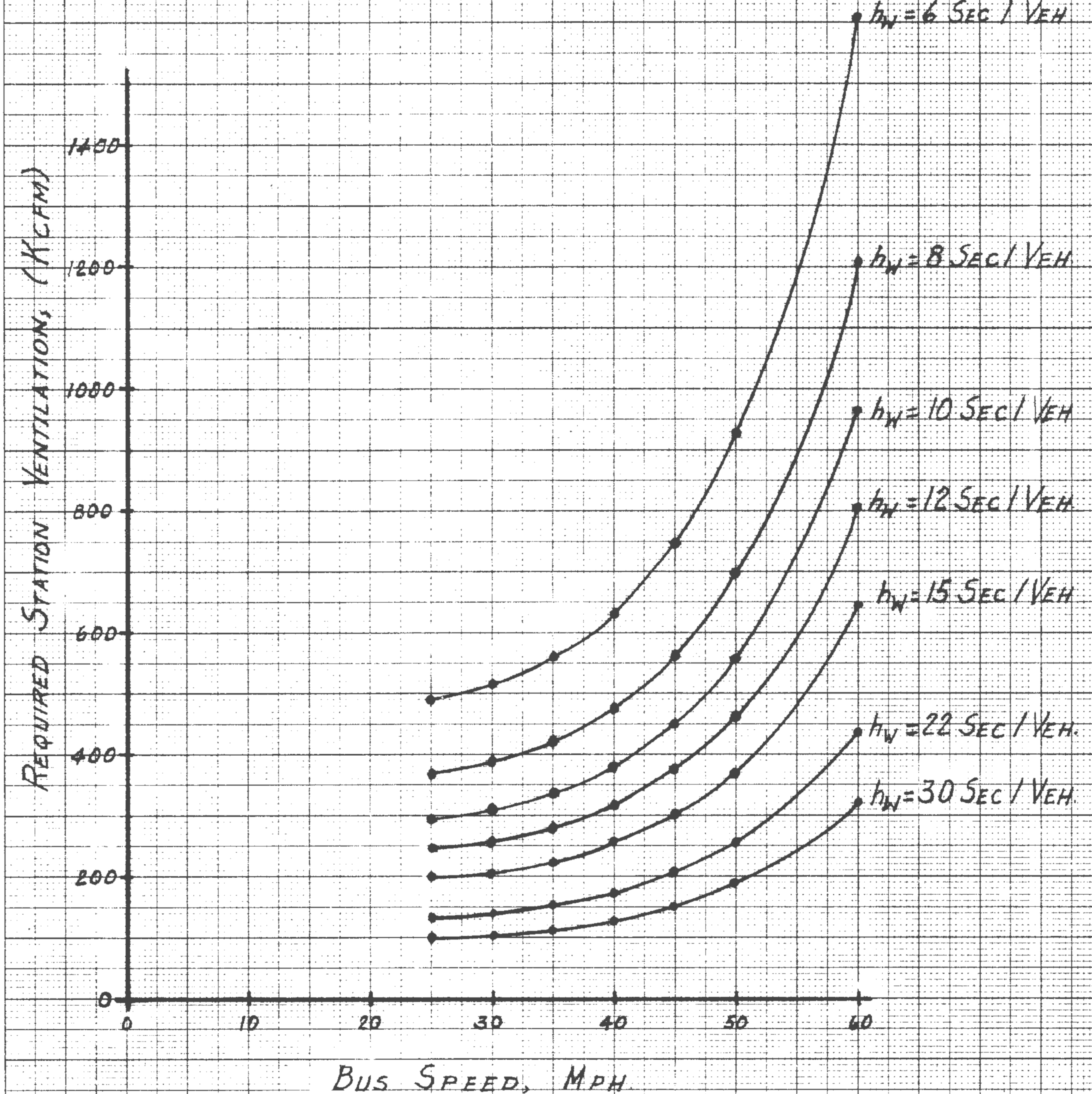



Figure 9 Required Station Ventilation

may be expected to walk against during an emergency. This air velocity can control the direction of spread of flames and smoke generated by a bus fire having a fire heat rate of about 600 million Btu/hour by overcoming buoyant forces assuming the grade is less than 3%. This fire heat rate is equal to about 4,800 gallons of gasoline per hour, is about 10 times that expected from a subway car fire, and is conservative estimate of what will occur.

## Normal Operations Ventilation Air Velocity Criteria

The maximum air velocity allowed in the tunnel during normal operations has been chosen to be 6000 fpm - the equivalent of a 935,000 cfm tunnel air flow. The basis for this selection is to limit the air velocities relative to the bus to those encountered during normal highway operations. For example, for a bus operating at 30 mph the air velocity in the bus-tunnel annulus would be 75 mph relative to the bus. The length and area of the turnaround shown in Figure 1 would have to be sized for the 6,000 fpm maximum air velocity.

## Alternative Ventilation System Concepts

The following ventilation system concepts are possible to meet the above air velocity criteria and to satisfy the project $NO_x$ criteria of 12.5 ppm:

1. A longitudinal ventilation system with the principle movement of air in the direction of traffic. Ceiling and wall mounted induction fans would be used to add up to 600,000 cfm to the bus piston effect ventilation which has a maximum of 335,000 cfm based on a bus speed of 40 mph and a headway of 6 seconds per vehicle. The system would have the ability to induce approximately 175,000 cfm of air in either direction in the bus tunnels for emergency ventilation. The tunnel section would have to be enlarged to accommodate the fans. The enlargements or "bubbles", would be about 75 feet long by 15 feet wide by 10 feet high. The fan size would vary inversely as the number.

2. A series of fan shafts with alternate supply and exhaust fans which would create a push-pull longitudinal ventilation system. The fans would be reversible for emergency ventilation and would be capable of meeting the 175,000 cfm emergency ventilation requirement for any section of tunnel. The spacing of the shafts would have to be adjusted to counteract the air flow imbalance caused by bus piston effect.

3. A full transverse ventilation system. This would be used if ventilation shafts were not feasible and would require a large increase in the tunnnel cross section area because of the addition of upper and lower air ducts. However, an advantage of this would be to confine a fire, thus the abovementioned emergency longitudinal ventilation capability would not be required.

These concepts are not affected by the air velocity of the outside environment (wind).

## 7. COST DATA

All cost data is based on 1978 prices. Construction costs are estimated using the following composite geology and unit prices:

Sedimentary rock - 48% ($2600/ft)

Alluvium above water table - 44% ($2600/ft)

Alluvium below water table - 8% ($3500/ft)

The costs of land acquisition, utility relocations, maintenance of traffic, etc. and the busway terminal station are not included.

### Baseline Cost for Tunnel Only (Not Including Ventilation)

The cost of the composite tunnel is $2675 per foot. Therefore the cost of the one-mile long bus tunnel approach (total tunnel length - two miles) is $28 million and that for the two mile long tunnel is $56 million. These figures also assume a flat grade tunnel with no entrance ramps.

## Emergency Ventilation Costs

The least expensive way to provide emergency ventilation to the bus tunnel is with a longitudinal ventilation system. The system would mount the fans in enlargements or "bubbles" in the tunnel structure, the cost of each enlargement being about $75,000.

For the one mile bus tunnel six axial flow fans having a capacity of 140,000 cfm each would be required for each tunnel. The total cost of the 12 fans, including enlargements, installation, electrical equipment, and appurtenances is $1,620,000.

For the two mile bus tunnel six axial flow fans having a capacity of 180,000 cfm each would be required for each tunnel. The total cost of the 12 fans, including enlargements, installation, electrical equipment, and appurtenance is $1,935,000.

## Normal Ventilation Costs - One Mile Tunnel

The following chart establishes the number of vane axial fans, their ventilation capacity, and costs including installation, required electrical equipment and appurtenances using the longitudnal ventilation concept at various bus headways with a bus speed of 40 mph:

| Bus Headway | No. of Fans | Cap. Per Fan - cfm | Total Cost |
|---|---|---|---|
| 22 | 12 | 100,000 | $1,620,000* |
| 19 | 12 | 150,000 | $1,790,000 |
| 15 | 12 | 225,000 | $2,124,000 |
| 12 | 12 | 280,000 | $2,762,000 |

* Provisions for emergency ventilation satisfy this condition.

The following chart establishes the number of vane axial fans, their ventilation capacity, and costs including installation, required electrical equipment and appurtenances using the push-pull ventilation concept at various bus headways with a bus speed of 40 mph:

| | | | Cost | | |
|---|---|---|---|---|---|
| Bus Headway Sec/Vehicle | No. Fan Shafts | No. & Capacity (cfm) of Fans Required | Fans | Fan Shafts* | Tot. Cost Fans and Fan Shafts & Ancillary Structures |
| 12 | 4 | 8 @ 140,000 | $ 670,000 | $2,000,000 | $2,670,000 |
| 8 | 6 | 12 @ 140,000 | 1,100,000 | 3,000,000 | 4,100,000 |
| 6 | 8 | 16 @ 280,000 | 1,950,000 | 4,000,000 | 5,950,000 |

*The depth of the fan shafts was assumed to be 80 feet (top of roadway to grade).

Normal Ventilation Costs - Two Mile Tunnel

The longitudnal ventilation system proposed above for emergency ventilation will not also provide sufficient ventilation for headways less than forty seconds, therefore, the push-pull ventilation concept should be used for the two-mile Tunnel. The following chart establishes the number of vane axial fans, their ventilation capacity, and costs including installation, required electrical equipment and appurtenances using the push-pull ventilation concept at various bus headways with a bus speed of 40 mph:

| | | | Cost | | |
|---|---|---|---|---|---|
| Bus Headway Sec./Vehicle | No. of Fan Shafts | No. & Capacity (cfm) of Fans Required | Fans | Fan* Shafts | Tot. Cost Fans and Fan Shafts |
| 30 | 3 | 8 @ 115,000 | $ 590,000 | $1,500,000 | $2,090,000 |
| 22 | 4 | 8 @ 155,000 | 650,000 | 2,000,000 | 2,650,000 |
| 15 | 6 | 12 @ 150,000 | 975,000 | 3,000,000 | 3,975,000 |
| 12 | 8 | 16 @ 142,000 | 1,280,000 | 4,000,000 | 5,280,000 |
| 8 | 10 | 20 @ 170,000 | 2,440,000 | 5,000,000 | 7,440,000 |

* The depth of the fan shafts was assumed to be 80 feet (top of roadway to grade).

ii. Transverse Ventilation

The cost of a full transverse tunnel ventilation system for bus headway of six seconds will be approximately two to two and one-half times the cost of using push-pull ventilation shafts.

Figures 10 and 11 depict cost vs. capacity for bus tunnels for the one-and two-mile-long approach tunnels to the busway terminal station.

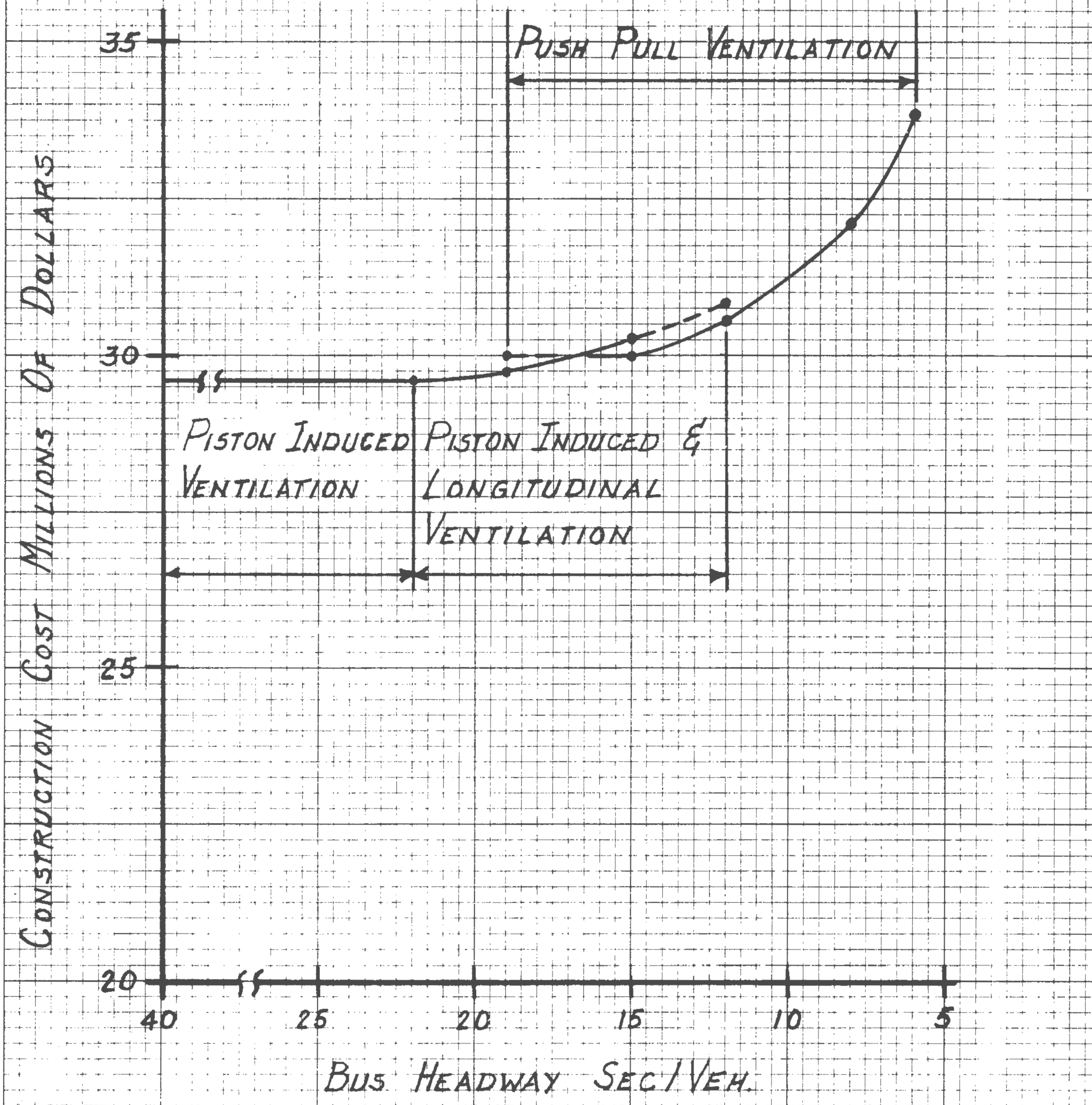



FIGURE 10 CONSTRUCTION COST VS HEADWAY FOR ONE MILE TUNNELS.

K+E 10 X 10 TO THE INCH • 7 X 10 INCHES KEUFFEL & ESSER CO. MADE IN U.S.A.

46 0700

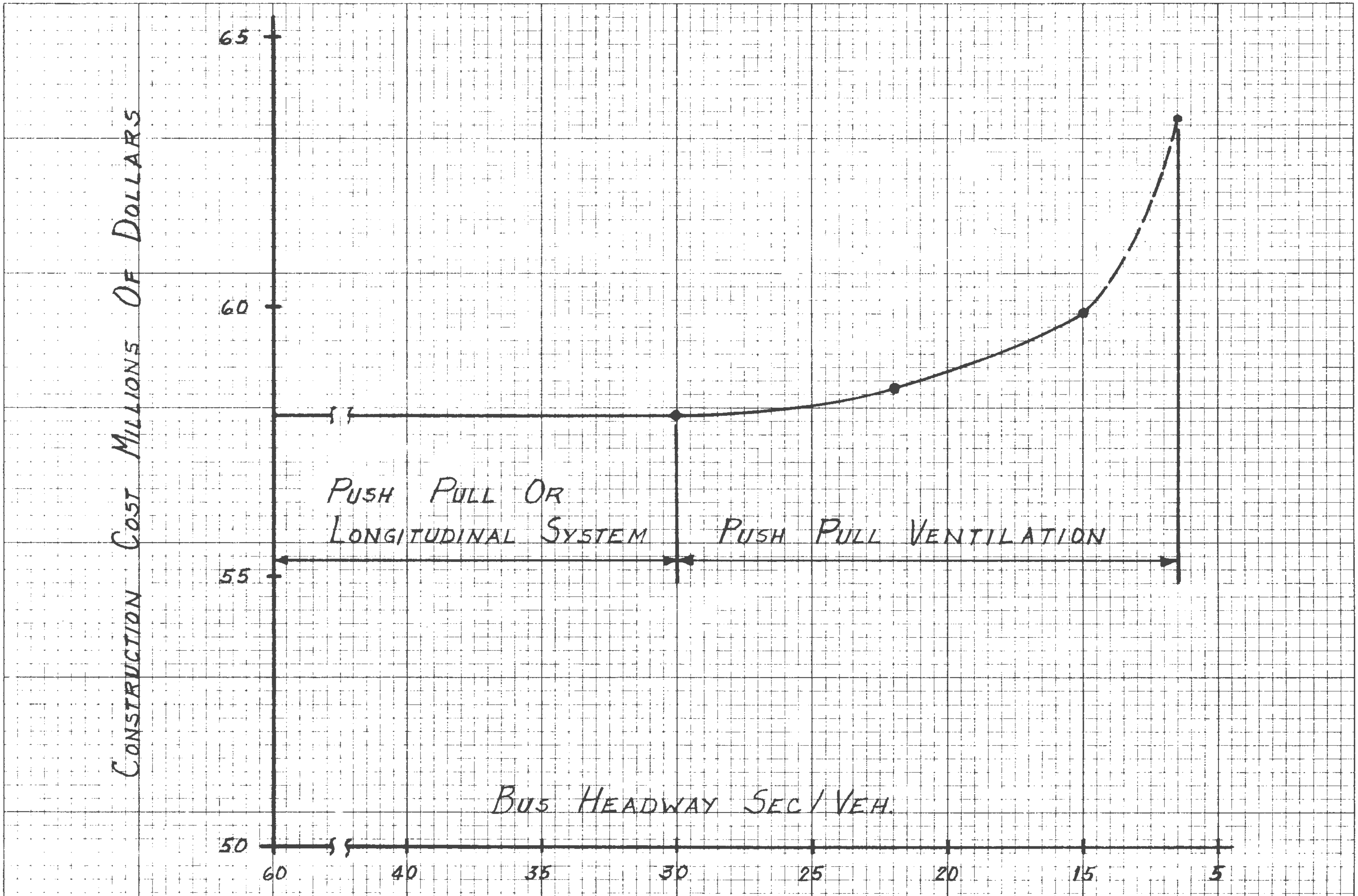



FIGURE 11 CONSTRUCTION COST VS HEADWAY FOR 2 MILE TUNNELS.